REPORT #
RRTAC 93-8

Oil Sands Sludge Dewatering by Freeze-Thaw and Evapotranspiration

Heritage Fund

Alberta

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RECLAMATION COUNCIL
Reclamation Research
Technical Advisory Committee

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Regulating surface disturbances in Alberta is the responsibility of the Conservation and Reclamation Council. The Council Chairman is from Alberta Environmental Protection. The Council oversees a reclamation research program, established in 1978, to identify the most efficient methods for achieving acceptable reclamation in the province. Funding for the research program is provided by Alberta's Heritage Savings Trust Fund, Land Reclamation Program.

To assist with the development and administration of the research program, the Council appointed the inter-departmental Reclamation Research Technical Advisory Committee (RRTAC). Committee members represent the Alberta Departments of Agriculture, Food and Rural Development, Energy, and Environmental Protection, and the Alberta Research Council. The Committee updates research priorities, reviews research proposals, organizes workshops, and otherwise acts as the coordinating body for reclamation research in Alberta.

Additional information on the Reclamation Research Program may be obtained by contacting:

Chris Powter, Chairman

Reclamation Research Technical Advisory Committee

Alberta Environmental Protection

3rd Floor, Oxbridge Place

9820 - 106 Street

Edmonton, Alberta T5K 2J6

(403) 427-4147

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By Freeze-Thaw and Evapotranspiration

by

R. L. Johnson

P. Bork

E.A.D. Allen

W.H. James

and

L. Koverny

Alberta Environmental Centre

Prepared for

SYNCRUDE CANADA LTD.

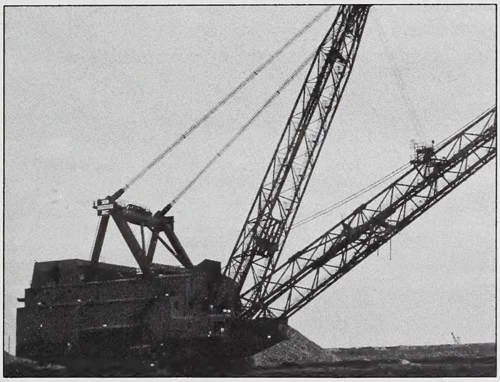
AND

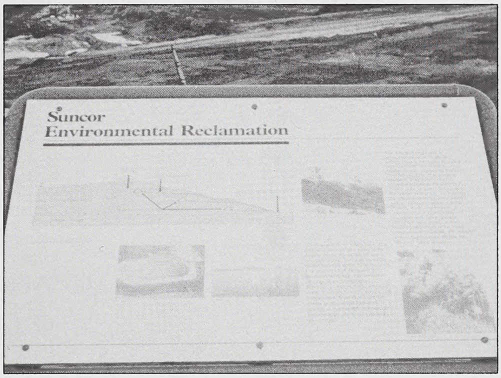
Oil Sands Reclamation Research Program

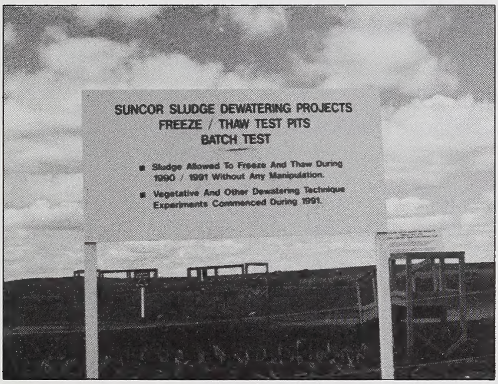
ALBERTA CONSERVATION AND RECLAMATION COUNCIL
(Reclamation Research Technical Advisory Committe)

1993

Oil Sands Reclamation Research Program







<u>**Members:**</u> Chris Powter (Chairman) - Alberta Environmental Protection; Martin Fung - Syncrude Canada Limited; Al Fedkenheuer - NOVA Corporation of Alberta; Paul Layte - Alberta Environmental Centre; Sam Takyi - Alberta Environmental Protection; Steve Tuttle - Suncor Inc.

DISCLAIMER

This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Conservation and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

The opinions, findings, conclusions, and recommendations expressed in this report are those of the authors and do not necessarily reflect the views of government or industry. Mention of trade names or commercial products does not constitute endorsement, or recommendation for use, by government or industry.

REVIEWS

This report was reviewed by members of RRTAC and the Oil Sands Reclamation Research Program Committee. Special thanks to George Lesko of Syncrude Canada Ltd. for his reviews.

FUNDING

Funding for this work was provided by the Alberta Heritage Savings Trust Fund, Land Reclamation Program through the Alberta Conservation and Reclamation Council. RRTAC wishes to thank Mr. George Lesko of Syncrude Canada Ltd. and Mr. Richard Johnson of the Alberta Environmental Centre for co-funding the project.

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EXECUTIVE SUMMARY

The dewatering of oil sands sludge is a major technological, economical, and environmental challenge to the oil sands industry of northeastern Alberta. Sludge is a mixture of small mineral particles (less than 44 μm in diameter), residual bitumen from the extraction process, and water. Sludge consolidates at the bottom of tailings ponds to approximately 30% solids in 2 years and will remain at this level of solids and water indefinitely. At 30% solids, sludge acts as a liquid; unstable and extremely low in strength. Approximately 25 million cubic metres of sludge at 30% solids are produced each year by the two operating extraction plants owned by Syncrude Canada Ltd. and Suncor Inc. More than 500 million cubic metres of sludge have been produced over the first 20 years these plants have operated.

The experiments detailed in this report show that it was possible to increase the solids content of sludge to 50% solids by adding three parts sand (tailings sand) to one part sludge. At 50% solids, the sand-sludge mixture was semi-plastic, but extremely weak. One thousand parts per million of lime were needed to keep the sand from segregating from the sludge. Drainage of sand-sludge mixtures, even under the pressure of self-consolidation, was slow and uneconomical. The sand-sludge mixture had to be dewatered to 85% solids content before its shear strength was sufficiently high to support machine traffic or the overboarding of more sand-sludge mixture. At 85% solids, the sand-sludge mixture had a shear strength in excess of 100 kPa.

Freezing and thawing sludge (without sand) caused the solids content to increase from 30% to 50%. Another 10% increase in solids content was achieved by several more cycles of freezing and thawing. At 50% solids, sludge was semi-plastic. Ditches or grooves ploughed into the sludge remained, but the shear strength was very low (less than 2 kPa). Sludge without sand needed at least 80% solids to have sufficient shear strength (more than 100 kPa) to support machinery traffic or sludge overboarding.

If snow was removed from the surface periodically, the sludge froze to 165 cm depth in one winter in Mildred Lake, the Syncrude Canada Ltd. plant and mine

site, approximately 40 km north of Fort McMurray, Alberta. If the snow cover was left in place, freezing was restricted to 30 cm. Laboratory and pilot-plant experiments showed that the amount of sludge that could be frozen in one winter could be increased by freezing the sludge in thin layers. Using this technique, a layer only a few centimetres deep was deposited and left to freeze for a day or two; as soon as it was frozen, a second layer was deposited. Layered freezing was also slightly more effective at dewatering sludge than freezing a pool of sludge from the top down.

The water released from the sludge during the thaw period rose almost immediately to the sludge surface. Surface water had to be drained away to allow further dewatering, either by evaporation or vegetation-controlled evapotranspiration. Standing water on the sludge surface prevented the establishment and growth of adapted vegetation by floating seeds, making the rooting medium unstable, or inhibiting oxygen flux to the root zone.

If the water was removed, two species of plants--reed canary grass and western dock--were well adapted to the sludge environment and capable of removing enough water from the sludge to dry it to 80% solids. Reed canary grass was the best adapted plant to both sludge and sand-sludge mixtures. Furthermore, reed canary grass grew from small sections of its own rhizome, known as sprigs. Starting plants on sludge with sprigs of reed canary grass may allow for large scale (hundreds of hectares) dewatering by vegetation. Sprigs were easy to spread, not subject to movement by wind or small amounts of water, and fast to establish new plants.

Sludge at 50% solids that was planted to reed canary grass was dewatered to 80% solids in one growing season. At 80% solids the sludge had a shear strength of 120 kPa and could support machine traffic of any kind or the overboarding of several metres of liquid sludge. However, the rapid removal of surface water and the quick establishment of a dense plant community were essential. Otherwise, dewatering during the summer months was minimal, less than a 5% increase in solids from May to October.

Sand-sludge mixtures were also dewatered by freezing and thawing. A 1 year dewatering cycle that included freezing and thawing and summer evaporation, but

no plant controlled evapotranspiration, increased the solids content of a 2-m deep sand-sludge mixture from 50% to 80% solids. Reed canary grass and western dock also grew well on sand-sludge mixtures and aided in dewatering, if the surface water was removed.

ACKNOWLEDGEMENTS

The research described in this report was carried out by numerous scientists and engineers over 6 years at several sites in Alberta. The person who contributed the most and is not listed as an author is Douglas Linman, soils technician, Alberta Environmental Centre. He shepherded the project in Vegreville, Edmonton, and 3 years in Fort McMurray. On the part of Syncrude Canada Ltd., Dr. George Lesko was scientific advisor, coordinator, and helpful collaborator. The original impetus for the project came from Mr. William Shaw, Engineer, Syncrude Canada Ltd.

A large group of technical and professional people at the Alberta Environmental Centre supported the oil sands sludge dewatering project. A few of the technicians were: Ivan Whitson, Dawnita Stewart, Sharon Novakowski, Sloane Dieken, Brian Soldan, Rick Komick, Rob Hughes, and Dale Regnier. Professional help was contributed by Paul Yeung, Tadeusz Kazmierczak, Donald Thacker, Reinhard Hermesh, Fred Dieken, Richard Milner, Chin Chu, and Arne Aasen. Paul Layte and Drs. R.S. Weaver, B. Bolwyn and M.A. Wilson actively supported the project throughout its duration.

Financial support came from three agencies: Alberta Environmental Centre, Syncrude Canada Ltd., and the Reclamation Research Technical Advisory Committee (RRTAC). RRTAC funding came through the Alberta Heritage Savings Trust Fund, Land Reclamation Program. RRTAC was first chaired by Dr. P. Zemkiewicz; the interim chair was Dr. G. Singleton, a soil mineralogist and reclamation specialist; and finally, Mr. C. Powter, who has supported this project through its failures and successes, and is now the RRTAC chairman.

Research at Mildred Lake, Syncrude Canada Ltd.'s plant location, was incorporated into existing operations by Don Provencal, Tailings Area Supervisor. He opened roads, levelled land, built dykes and excavated pits. Dr. Chris Marsh, Julian Coward and Ted Lord helped establish each new experiment in Mildred Lake.

This report was typed through many editions by Lorraine Yakemchuk, Elaine Cannan, Barb Dreger and Charlene Petryshyn. With good grace, they handled the chore of managing authors and their often illegible writing. The final edition has been typed by Charlene Petryshyn.

Thanks to Bernie Goski, Brenda Dew and Ivan Dmytriw for finalizing the figures and coordinating the assembly of the report. Also, thank you to Susan Paquin for her assistance in editing this report.

DEDICATION

This report is dedicated to Gerry Wheeler, a former plant taxonomist at the Alberta Environmental Centre. Gerry died on November 8, 1989, near Fort McMurray, in a traffic accident.

In 1984, Gerry was asked to make a list of possible plants that could grow in oil sands sludge and use enough water to contribute to its desiccation. He listed 48 species. He was then asked to predict which of these would be most likely to excel. He selected two--western dock and reed canary grass. After 6 years of careful experimentation, these two species are still the two best choices.

With Gerry's death, plant ecology lost one of its most able practitioners.

1.0 INTRODUCTION

The extraction of bitumen--a viscous, non-fluid oil occurring in oil sands at reservoir temperatures--is accomplished most economically by the four-decade-old, Clark Hot Water Process. In its simplest form, the process consists of mixing a small amount of hot water with oil sands in a conditioning vat and then flooding the mixture with hot water. The bitumen rises to the surface, is skimmed off, and is refined into synthetic oil (Carrigy 1986). The rest of the mixture--water, sand, fines and residual oil--is slurried away from the extraction site into tailings ponds.

The disposal of vast quantities of slurried materials is an enormous waste management problem. In Fort McMurray, Alberta, two extraction and upgrading plants produce approximately 200,000 barrels of synthetic oil per day from 400,000 tonnes of oil sands. The tailings stream amounts to 180 million tonnes per year and requires approximately 29 square kilometres of tailings pond area to contain it.

The most intractable component in the tailings stream, in regard to its permanent disposal, is sludge--a mixture of fine mineral particles, water, and residual bitumen. When the entire tailings stream is pumped from the extraction area, it contains between 50% and 55% solids. The sand portion of the solids segregates from the slurry upon deposition at the edge of the tailings pond and is used to build the pond dykes. A "fines" stream (thin sludge), composed of silt and clay, small amounts of bitumen, and water, flows into the pond. The solids content of the fines stream is approximately 5% (Scott and Cymerman 1984). The mineral fines, less than 30 µm in effective settling diameter (Scott et al. 1985), settle out and consolidate to a solids content of 20% to 30% within 2 years. More than one-half of the supernatant water in the tailings pond is returned to the plant for reuse. Consolidation of the sludge at the bottom of the tailings pond (Figure 1) from 20% or 30% solids to 80% or 90% solids is extremely slow, predicted to take tens of thousands of years, if left to mature under natural conditions.

J.D. Scott, a professor of geotechnical engineering at the University of Alberta in Edmonton, has investigated the behavior of oil sands sludge for more than 10 years. He summarizes the essential problems of sludge management (Scott et al. 1985):

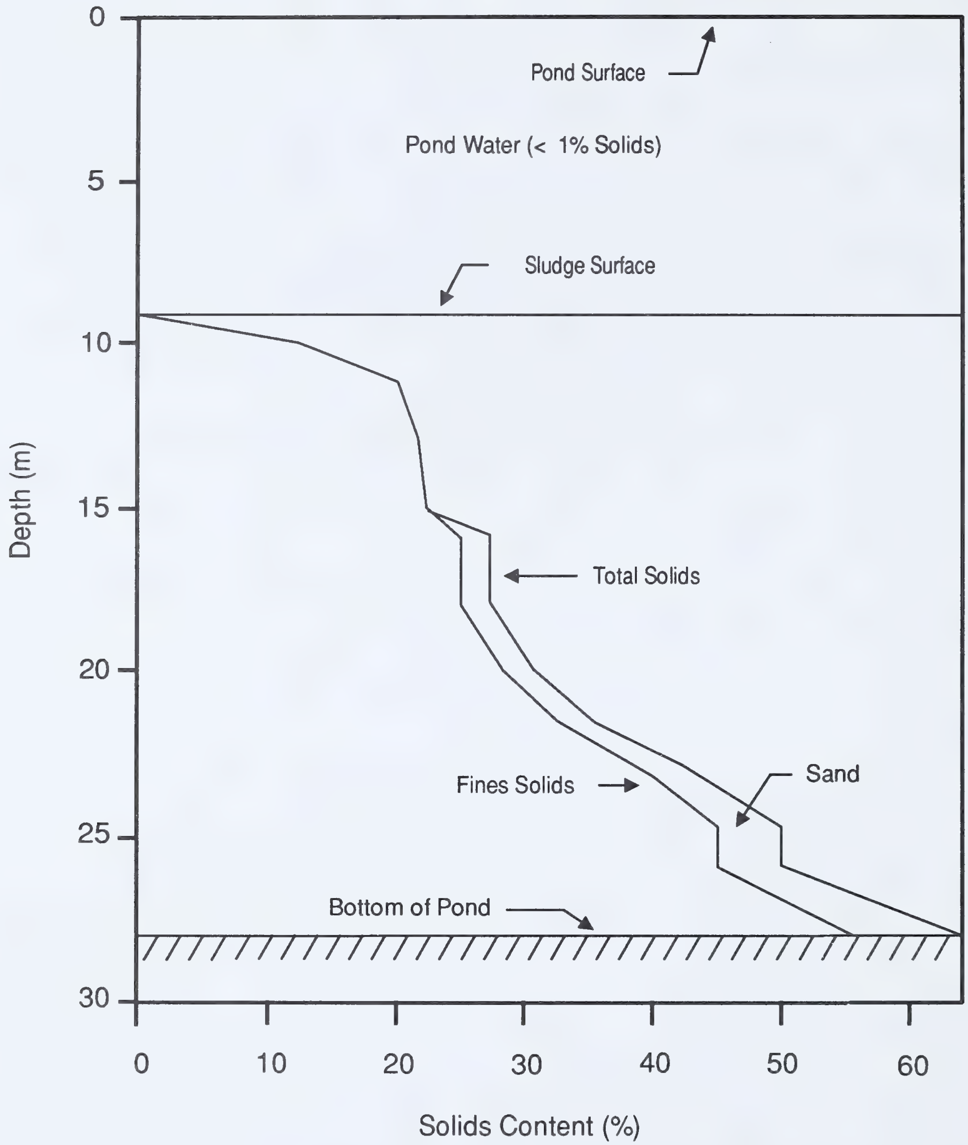

Figure 1. Diagramatic representation of the relationship between solids content and depth in the Syncrude tailings pond at Fort McMurray, Alberta. Source: Scott and Cymerman (1984).

> "There remains a misconception in the industry that oil sands sludge does not settle well. This is not true. The sludge originally enters the pond at a solids content of 5% and settles very effectively to 20-30% solids content within a short time. To consolidate to 30% solids content ... requires a further period of a year or two, and thereafter consolidation processes are extremely slow .... Sludge settles well despite the poor pH (8-8.5) and well-dispersed state due to the extraction process. The true problem is the slow rate of consolidation once the sludge solids content exceeds 30%, at which point the sludge is still of a consistency similar to chocolate custard."

The traditional approach to the disposal of fine-grained waste--storage in large impoundments surrounded by dykes--is unsatisfactory in Fort McMurray for economic and environmental reasons. They are: the sludge ponds cover large areas of mineable oil sands; the cost of pond construction and maintenance is high; there are serious environmental objections to ponds that are physically unstable (McRory 1982) and incapable of supporting the weight of animal or machine, and are hazardous to wildfowl; and the slow rate of consolidation means that natural stabilization will be delayed over millenia. The ideal solution would satisfy the twin needs of economic acceptability and technical feasibility on a large scale. The sludge "should be solidified, placed in the mined out area, and the surface reclaimed to the original state" (Scott and Cymerman 1984).

There are two known techniques for solidifying wet slurries which may be both economic and technically feasible: (1) wet coarse waste addition (Scott and Cymerman 1984); and (2) drying (Beardsley 1976) or drying accompanied by drainage (Ihle et al. 1983; Vogt and Stein 1976). The first alternative mixes coarse and fine-grained solids in water, causing the non-consolidating fines to be captured in the sand grain voids. In its simplest form, the first option would involve mixing sludge consolidated to 30% solids with sand and depositing the slurried mixture in the mined-out pit. If the mixture did not segregate (i.e., the sand did not separate from the fines) and

if self-consolidation to 80% solids were fast enough, this technique would be simple and relatively inexpensive. The disadvantages have been shown to be the lack of control of segregation, the uncertainties regarding rates of self-consolidation, and the monumental volume of sand needed to trap relatively small quantities of sludge (Scott and Cymerman 1984).

Syncrude Canada Ltd. has evaluated other mixing methods and is currently focusing effort on a codisposal technique whereby overburden (Clearwater Formation) is pumped using sludge as the transporting medium. The final deposit consists of a soft clay formed by the mixing of sludge and clay shale overburden, which can absorb a lot of water while still maintaining adequate strength for reclamation purposes. The runoff, which has additional clay particles resulting from lump degradation, is recirculated.[1]

Thin layers of fine-grained slurries has been dried primarily in desert climates. The tailings are sent to a containment area where the solids settle and water is removed by decantation. A load-bearing solid waste is produced by evaporating the water during the final stages of dewatering. The addition of a sand bed for drainage underneath the fine-grained slurry decreases the dewatering time and allows thicker layers of clay tailings to be solidified (Ihle et al. 1983; Sparrow 1978; Sparrow and Ihle 1978). Although the climate of Fort McMurray cannot be described as arid, the use of summer evaporation to dewater sand-sludge mixtures and pure sludge needs to be evaluated.

Most drying operations use very shallow (less than 20 cm) depths of fine-grained materials. The enormous volume of sludge generated in Alberta's Athabasca oil sands area (25×10^6 m^3/year) necessitates a system capable of handling a layer at least 2-m thick per year. The only technique where wet materials are dried to this depth in short time periods is polder reclamation, pioneered and practised around the world by Dutch soil scientists and engineers (Volker 1982). The ocean bottom sediments with which polder formation begins have an extremely high water content, are low in hydraulic

[1]Personal communication, T. Lord, Syncrude Canada Ltd.

conductivity, and have a low bearing capacity (Rijniersce 1982). Their similarity to oil sands sludge in these physical properties is remarkable.

The dewatering process in polders, known as "soil ripening", is accelerated by adding plants capable of using large amounts of water (evapotranspiration) and developing deep root systems. The stabilization of phosphate tailings in Florida also uses plants, mainly cypress hardwoods and riparian forest species (Reusch 1983). Both Florida and The Netherlands have climates with more annual precipitation than potential evapotranspiration; therefore, the formation of root-bound surfaces causes as much stabilization of weak soils as does the loss of water by evapotranspiration.

This report details the experiments and results carried out by scientists and engineers at the Alberta Environmental Centre from fall 1984 to fall 1990 on the dewatering of oil sands sludge. In the beginning of the project, from 1984 to 1986, work centred on the dewatering of sand-sludge mixtures, because their behavior had been studied and characterized, and engineering design was well advanced. Experiments at the Alberta Environmental Centre focused on selecting plants capable of dewatering these mixtures faster than their natural rate of consolidation. Concomitantly, soil scientists studied the physical behavior of sand-sludge mixtures under the influence of evaporation and drainage. The occurrence of segregation, cracking, and crust formation in the field became important criteria for adapting biological dewatering to large-scale projects. To our knowledge, this is the first report in the scientific literature on the use of plants to enhance the rate of dewatering and to stabilize oil sands sludge.

Another technique of dewatering oil sands sludge, freezing and thawing to cause water release, was tested at the Alberta Environmental Centre in the winter of 1986-87. The advantages of developing a freeze-thaw approach to dewatering pure sludge are numerous: it is inexpensive because there is no need to handle sand or add lime; it can use existing slurry transport facilities, such as pumps, pipelines, and tailings ponds; and it fits into a logical cycle for northern climates where winter is used for freezing, spring brings the thaw and partial dewatering, and summer evapotranspiration completes the process. The major uncertainties are the volumes that can be frozen each winter, the

efficient drainage of surface water, and the final dewatering that will leave a load-bearing surface.

The idea of using freeze-thaw cycles to dewater pure sludge in the fall of 1985-86 led to a redirection of research at both the Alberta Environmental Centre and in field experiments at Syncrude Canada Ltd.'s plant at Mildred Lake near Fort McMurray. The latter part of this report documents the results of these experiments and describes the progress that was made.

It now appears possible that before the end of the century a technique will have been developed to economically dewater oil sands sludges on a massive scale to the point that the reclaimed surface will support a plant and animal community similar to that existing prior to disturbance.

2.0 THE PROPERTIES OF OIL SANDS SLUDGE AND TAILINGS SAND

The two kinds of materials used throughout the experiments and tests discussed in this report were sludge and tailings sand. This section shows how the materials varied in their physical and chemical properties and provides the basic information necessary to interpret their behavior during dewatering. In addition, Clearwater shale--a mineral overburden associated with oil sands in northeastern Alberta--was analyzed. Some experiments resulting from large-scale dredging tests carried out by Syncrude Canada Ltd. in 1985-88 used a combination of sludge and Clearwater shale.

2.1 PHYSICAL PROPERTIES

Determinations of void ratio, particle size distribution, and hydraulic conductivity were conducted on the tailings sand. The saturation percentage and particle size analysis of sludge and shale from different origins were measured. The hydraulic conductivity of sludge is reported in Section 3.1.

2.1.1 Materials and Methods

Tailings sand was collected from many locations on the dyke surrounding Syncrude's tailings pond. Recent (deposited less than 1 month prior to sampling) and old sand deposits were sampled in bulk lots. Composite samples were taken from bulk lots for analysis.

The tailings sand was oven-dried (130°C for 24 h) before its physical properties were analyzed. It was then crushed with a wooden mallet to break apart aggregations formed by intergranular bonding.

Three tests were performed on tailings sand. The first measured the void ratio. The density of a dry sand sample was determined using a specific gravity balance. Its mineral specific gravity was 2.65 g/cm^3.

The second test measured the particle size distribution of tailings sand. Approximately 200 g of sand was oven-dried, weighed, and placed into a sieve stack. The sieve stack had progressively smaller screen sizes from top to bottom with the

following mesh dimensions: #10 (2 mm); #30 (600 µm); #100 (150 µm); #200 (75 µm); and a pan to catch all particles less than 75µm. The sieve stack was shaken on a Ro-Tap testing sieve shaker for 20 min. The weights of material retained on each sieve and in the pan were recorded.

The third test measured the hydraulic conductivity (Klute 1965) of the tailings sand. Three bulk densities (1.4, 1.5 and 1.6 g/cm^3) of four replicates each were created by compressing 200 g of the tailings sand in plexiglass cylinders to a predetermined volume. The sand columns were then saturated by placing them in distilled water overnight. With a filter paper placed on top of the sand column to prevent disturbance during infiltration, an inverted 250 ml volumetric flask with distilled water was placed over the cylinder to maintain a constant head of 10 cm of water. The outflow of water was measured by a graduated cylinder every day for 5 days.

Saturation percentage and particle size analysis conducted on the sludge and shale followed standard procedures in McKeague (1978) and USDA (1954).

Several lots of oil sands sludge were used in experiments at the Alberta Environmental Centre (AEC) and at Mildred Lake on Syncrude Canada Ltd.'s site near Fort McMurray. The first lot consisted of 200 L delivered to AEC in autumn 1984 by Mr. William Shaw, Syncrude Research, Edmonton. Later in 1985, he supervised the pumping of another 20,000 L from the main tailings pond of which 8,000 L were delivered to AEC. In 1987, Syncrude Canada Ltd. pumped more sludge from the tailings pond to a holding pond at Mildred Lake. Approximately 10,000 L were delivered to AEC. Finally in 1988, Syncrude Canada Ltd. pumped very large amounts of sludge (>100,000 L) from the tailings pond to holding pits for a dredging experiment they were conducting. AEC used 20,000 L for experiments at Mildred Lake and shipped 17 barrels (200 L/barrel) to Vegreville.

The Clearwater shale used for analysis was sampled from a pit close to the tailings pond at Mildred Lake in summer 1987 during a dredging test.

Saturation percentage and particle size analysis conducted on the oil-free sludge (toluene washed) and shale followed standard procedures in McKeague (1978) and USDA (1954).

2.1.2 Results

The density of the loose sand was 1.44 g/cm^3. The void ratio was computed as follows:

$$e = \left(\frac{P_s}{P_d}\right) - 1 \qquad \textit{(Equation 1)}$$

where

e = void ratio of loose sand

P_s = density of sand mineral (g/cm^3)

P_d = density of loose, dry sand (g/cm^3)

e = (2.65/1.44)-1 = 0.84

The grain size distribution data from two composite samples are tabulated in Table 1. The cumulative percentage of material passing or retained on each sieve was used to develop the grain size distribution curve in Figure 2.

The coefficient of uniformity was calculated using the equation:

$$C_u = \frac{D_{60}}{D_{10}} \qquad \textit{(Equation 2)}$$

where

C_u = coefficient of uniformity

D_{60} = grain diameter corresponding to 60% finer passing by mass (mm)

D_{10} = grain diameter corresponding to 10% finer passing by mass (mm)

From Figure 1

D_{60} = 0.154

D_{10} = 0.085

C_u = 0.154/0.085 = 1.81

Table 1. Grain size distribution of tailings pond sand.

US sieve #	Aperture (μm)	Sample 1 (g)	Sample 1 (%)	Sample 2 (g)	Sample 2 (%)	Average (%)	Cumulative % retained	Cumulative % passing
10	2,000	0.2	0.1	0.5	0.2	0.15	0.15	99.85
30	600	3.2	1.6	2.9	1.4	1.50	1.65	98.35
100	150	88.8	44.4	84.4	42.1	43.25	44.90	55.10
200	75	94.5	47.3	99.2	49.5	48.40	93.30	6.70
Pan	<75	13.1	6.6	13.6	6.8	6.70	100.00	0.00
Total		199.8	100.0	200.6	100.0	100.00		

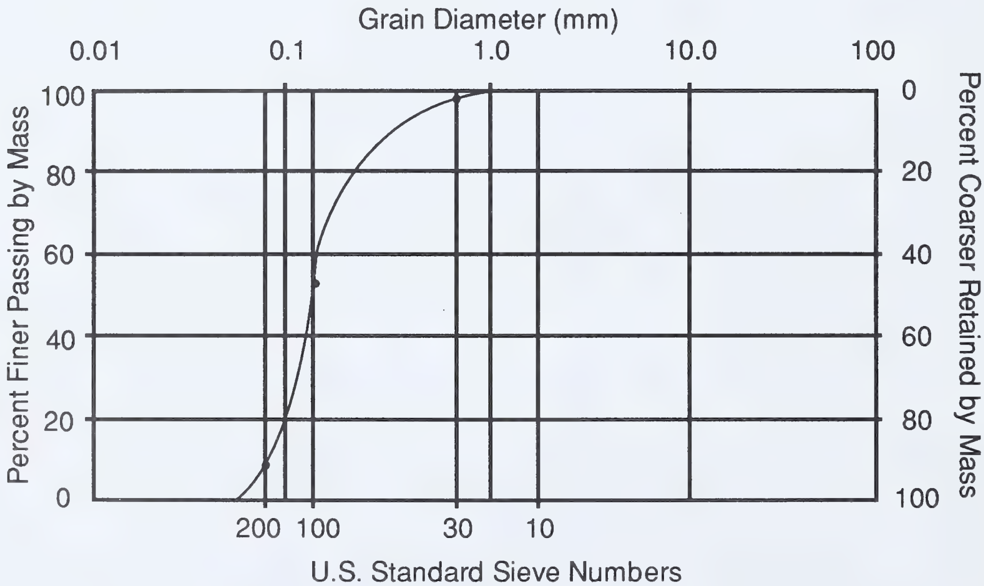

Figure 2. Grain size distribution curve of tailings pond sand.

Since the coefficient of uniformity was less than 2, it was classified as a very well sorted sand (or very poorly graded sand). To complete the classification of the sand under the Unified Soil Classification System (USCS), the material passing the #200 sieve was also tested. Personnel at Syncrude Canada Ltd. have shown that the finer material is silty. Therefore, under the USCS, the Syncrude sand was classified as an SP-SM borderline soil, or specifically a poorly graded (well sorted), silty, fine sand.

Comparisons of parameters between Syncrude sand and published data of other cohesionless soils have provided an approximation of the angle of internal friction for Syncrude sand. From Holtz and Kovacs (1981) and the calculation of the void ratio, together with the coefficient of uniformity for loose Syncrude sand, it was inferred that the angle of internal friction was 34°.

Measured hydraulic conductivity rates of the tailings sand were 0.83, 0.84 and 0.88 cm/day for bulk densities of 1.6, 1.5 and 1.4 g/cm^3, respectively. Hydraulic conductivity rates (K) were calculated by the following:

$$K(cm/day) = \frac{Q \cdot L}{A \cdot t \cdot H} \qquad (\textit{Equation } 3)$$

where

Q = water outflow (cm^3 or mL)

L = thickness of the sand column (cm)

A = cross sectional area of the sand column (cm^2)

t = time (days)

H = hydraulic head difference (cm), measured from the water level to the bottom of the sand column.

The physical properties of oil sands sludge and overburden Clearwater shale are presented in Table 2. The saturation percentages were 75% and 78%, respectively. Both sludge and shale samples had high levels of mineral fines and belonged to the clay and heavy clay textural classes.

Table 2. Physical properties of oil sands sludge and Clearwater shale.

Sample	Origin	Saturation percent	Particle sizes[6]			Texture
			>50 μm[3]	2 to 50 μm[4]	<2 μm[5]	
				(%)		
Sludge	T.P.[1]	75[2]	26	27	47	C
Shale	Clearwater	78	11	22	67	HC

[1] Tailings pond at Syncrude's Mildred Lake site.
[2] The average saturation percent for two sludge samples.
[3] sand
[4] silt
[5] clay
[6] Particle size distribution was determined by the hydrometer method (Bouyoucos 1962).

2.2 CHEMICAL PROPERTIES

Soluble anions, soluble sodium and potassium, electrical conductivity, and pH were measured on the oil sands sludge, tailings sand, and Clearwater shale. Oil sands sludge was also measured for soluble calcium and magnesium and all of the exchangeable cations.

Water quality data of the tailings pond and sludge pore water were obtained from the Soils Laboratory at the Alberta Environmental Centre and Syncrude Research, Edmonton.

2.2.1 Materials and Methods

The samples of sand, sludge, and shale used in the chemical analysis were from the same composite samples used in the physical analysis. All chemical tests conducted in the Soil Analytical Laboratory of the Alberta Environmental Centre followed standard procedures in McKeague (1978) and USDA (1954). The bitumen content of oil sands sludge was determined using the method in Yeung and Johnson (1986). Soil reaction (pH), electrical conductivity (EC), soluble cations, and anions were determined

from saturated paste extracts. Exchangeable cations were extracted with neutral ammonium acetate and determined by flame photometry and atomic absorption.

2.2.2 Results

Table 3 presents the chemical properties of oil sands sludge, Clearwater shale, and tailings sand. Oil sands sludge was alkaline, (pH 8.2) owing to the caustic hot-water extraction method used to remove bitumen, and contained a residual bitumen content of 4.0% (weight bitumen over dry weight solids). Soluble salt concentrations (EC = 2.0 to 3.7 dS/m) and nutrient contents (7 ppm N, 2 ppm P and 13 ppm K) were low. Clearwater shale was also alkaline (pH 8.1), but contained a much higher concentration of soluble salts (EC = 11.6 dS/m). As a result, the dredge sludge, a mixture of tailings pond sludge and Clearwater shale, contained a medium level of soluble salts (EC = 3.4 to 5.3 dS/m) and had a moderately high pH of 8.2 to 8.6.

Although the soluble sodium concentration in the oil sands sludge and tailings sand was higher than the total of calcium, magnesium, and potassium ions, the overall concentration of sodium was considered to be low. The soluble sodium concentration in Clearwater shale was higher (10.2 meq/100 g) than the others.

All materials, except tailings sand, contained considerable amounts of soluble chloride. Dredge sludge occasionally yielded much higher levels of soluble chloride (1,045 ppm). Sulphate concentrations approximated those normally found in soil, except that of the Clearwater shale, which was high (7,688 ppm). This is not uncommon, as saline geological materials in Alberta often contain much soluble sulphate.

The analytical results of surface water from the tailings pond and sludge pore water are presented in Table 4. The results were surprisingly similar, given that two labs (AEC and Syncrude Canada Ltd.) measured sludge pore water from samples taken from different parts of the tailings pond in different years, and MacKinnon (1986) measured tailings pond surface water alone.

Table 3. Chemical properties of oil sands sludge from different origins (no replication).

Sample	Origin	pH	Electrical Conductivity (dS/m)	Soluble Cations (meq/100 g)				Soluble Anions (ppm)		Exchangeable Cations (meq/100 g)			
				Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	$SO4^{2-}$	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
Sludge	T.P.[1]	8.3	3.7	0.2	0.1	2.9	0.1	526.7	160.5	8.1	4.2	1.5	0.5
Sludge	T.P.	8.2	2.0	0.1	0.1	1.7	<0.1	470.8	70.5	7.3	4.2	0.7	0.5
Sludge	Dredge[2]	8.2	5.3	0.1	0.1	1.8	<0.1	1,045.0	152.0	28.5	4.8	3.1	0.5
Sludge	Dredge	8.6	3.4	ND[3]	ND	2.4	<0.1	456.0	310.0	ND	ND	ND	ND
Shale	Clearwater	8.1	11.6	ND	ND	10.2	0.2	110.4	7,688.0	ND	ND	ND	ND
Sand	T.P.	9.0	1.8	ND	ND	0.4	<0.1	70.4	160.4	ND	ND	ND	ND
Sand	T.P.	8.3	0.9	ND	ND	0.2	<0.1	78.8	128.8	ND	ND	ND	ND

[1] T.P. Tailings pond at Syncrude's Mildred Lake site.
[2] Mixtures of tailings pond sludge and Clearwater shale.
[3] ND not determined; no analysis conducted.

Table 4. Chemical properties of sludge pore water after freezing and thawing and free water on the surface of tailings pond.

Property	Sludge pore water Units	AEC.S[1] (n = 3)	SCL[2] (n = 4)	Tailings Pond[3] (n = unreported)
pH		8.5	8.4	8.1
Conductivity	dS/m	1.2	1.1	1.8
Calcium	ppm	4.9	5.3	7.0
Potassium	ppm	9.2	18.1	10.0
Magnesium	ppm	4.2	4.8	4.0
Sodium	ppm	356	307.8	440.0
Chloride	ppm	93.4	82.2	126
Bicarbonate	ppm	ND	616.0	580
TDS[4]	ppm	ND	ND	1,200
COD[5]	mg/L	ND	ND	422
Turbidity	ppm	ND	ND	680
Oil & Grease	ppm	ND	ND	200

[1] Sludge pore water analyzed in the Soils Laboratory, AEC.
[2] Pore water from sludge at 16 to 20-m depth in Syncrude's tailing pond. Values are averages over 4 years (1980-83) from the same depth interval. Solids content increased from 16% to 27% during this time. Analyses done at Syncrude Research, Edmonton.
[3] Water from surface of Syncrude's tailings pond. See MacKinnon (1986).
[4] Total dissolved solids.
[5] Chemical oxygen demand.
[6] ND not determined; no analysis conducted.

3.0 THE PHYSICAL BEHAVIOR OF SAND-SLUDGE MIXTURES

For years geotechnical engineers have worked on the sedimentation and consolidation of fine-grained materials produced by the oil sands extraction plants near Fort McMurray. (Scott and Cymerman 1984; Scott et al. 1985). They have concentrated

their studies on the change in properties of sand-sludge mixtures as the water content decreases from the liquid to the plastic and finally to the shrinkage limit. With a remarkably simple tool, termed the sands-fines-water diagram, Scott and Cymerman (1984) developed a predictive method for evaluating the principal physical properties of various sand-sludge mixtures, namely, the sedimentation-consolidation boundary, the segregating-nonsegregating boundary, the pumpable-nonpumpable boundary, the liquid-solid boundary, and the saturated-unsaturated boundary. The latter two boundaries are critical for determining the consistency at which the sand-sludge mixture can be capped with more solid material and reclaimed to productive use.

The liquid-solids boundary for any ratio of sand and sludge between 1:4 and 4:1 is more than 70% and less than 80% solids (Scott and Cymerman 1984). Therefore, if the mixture falls between these two ratio limits and has more than 80% solids, the surface will be dry and capable of bearing a load.

The saturated-unsaturated boundary defines the percent solids in the mixture, at different sand-sludge ratios, where saturated conditions cease and unsaturated conditions begin. In the words of Scott and Cymerman (1984) "... it is the minimum void ratio ... after gravity drainage."

The critical problems of defining the physical properties of sand-sludge mixtures do not stop here, however. It is important to quantify the rate of drainage of these mixtures to understand the operational problems of dewatering on a large scale. Calculations of area, tonnage, time, and all the resulting requirements of manpower, equipment, energy, and supplies will depend on these characteristics. Furthermore, consolidation tests, as now performed, take several years to carry out. If a potential treatment, such as a calcium amendment or partial bitumen removal, is proposed to enhance consolidation times, confirmatory tests are laborious and time consuming.

The dewatering project at the Alberta Environmental Centre modified an Australian laboratory technique used on soils and slurries to quantify the drainage and consolidation characteristics of sand-sludge mixtures. As a result of these studies (Section 3.1) it is possible to characterize the effect of any treatment on these physical properties

in a few weeks in the laboratory. Section 3.2 examines the effect of calcium amendments on the hydraulic conductivity of sand-sludge mixtures.

3.1 THE DEWATERING OF SAND-SLUDGE MIXTURES BY DRAINAGE AND EVAPORATION

The enormous amount of sludge generated during oil sands processing--25 x 10^6 m^3 per year--means that dewatering must be inexpensive to be used commercially. Vacuum and pressure filters (Hegyan and Zugates 1976), centrifuges (Orphanos 1975; Van den Broeck 1982), and belt filters (Fischer and Schill 1981; Lymberg 1981) used to dewater coal tailings employ mechanical equipment with high capital and operating costs. Furthermore, dewatering after mechanical processing is often necessary to obtain a completely solid product. These mechanical systems are obviously inappropriate for the oil sands industry.

Dewatering on sand drainage beds is used for sewage (Beardsley 1976), waste water sludge (Novak and Montgomery 1975), and bauxite tailings from the Bayer process (Vogt and Stein 1976). In its simplest form, saturated fines are deposited on free-draining beds, and water is lost through drainage, supernatant pump-off, and evaporation. The major limitations of this approach to dewatering are the tenaciousness with which the tailing fines hold on to their water, the depth to which drainage and evaporation operate, and the area needed for an extremely large dewatering operation (Ihle et al. 1983; Sparrow and Ihle 1978).

The drainage and evaporation properties of a tailings sand-sludge mixture in Fort McMurray generated by Syncrude Canada were characterized using the theory developed by Sparrow (1978).

3.1.1 Materials and Methods

The dewatering equation has drainage and evaporation components because water is lost by drainage into sand and by evaporation from the surface. Therefore, the dewatering equation is written as (Sparrow 1978):

$$i = S\sqrt{t} + E \qquad \textit{(Equation 4)}$$

where

i = cumulative water loss (cm)

S = sorptivity of the mixture (inversely related to hydraulic conductivity) (cm/$\sqrt{h}$)

t = time (h)

E = evaporation rate from surface (cm)

Dewatering is expected to occur by both evaporation and vertical drainage until the water content at which drainage ceases is reached. Further dewatering is by evaporation alone. If drainage does not occur, the $S\sqrt{t}$ term is zero.

The dewatering equation assumes that all water moving to the surface of the tailings is removed by pump-off, surface drainage, or drainage through cracks in the solids. It is also assumed that rainwater is removed from the surface soon after it falls. That is, there is no free water above the solids. Therefore, E is total evaporation rather than net evaporation (total evaporation minus rainfall).

The properties of the sand and sludge used in this study are reported in Sections 2.1.2 and 2.2.2. Sand was mixed with wet sludge in a ratio of 3:1 (dry weight solids basis) and sufficient tap water was added to bring the mixture to 55% solids. The ionic constituents of the sludge were concentrated enough to overshadow any influence of the tap water. One thousand parts per million of calcium hydroxide ($Ca(OH)_2$) were added to the mixture to prevent the segregation of sand and sludge.

The dewatering properties of the mixture were determined from a series of constant-pressure filtration tests. These results were used to calculate the expected variation with time of the solids content of the sand-sludge mixtures during dewatering. When pressures less than 0.2 bars were required (i.e., 0.033, 0.066 and 0.1 bars), the apparatus consisted of a modified "hanging water balance" (Berliner et al. 1980). A glass filter funnel (diameter 3 cm, height 5 cm) fitted with a sintered glass, porous plate (bubbling pressure 1.8 bar) was filled with approximately 120 g of a 3:1 sand-sludge mixture and suspended from an electronic balance (Figure 3). The bottom outlet of the

filter funnel was connected to a Mariotte bottle by flexible tubing. The tubing and Mariotte bottle were filled with distilled water and leveled with the porous plate of the filter funnel. The Mariotte bottle was then lowered to the desired height to achieve the required pressure (e.g., 0.033 bar = 33.66 cm H_2O). The water loss from the sample of the sand-sludge mixture in the funnel was monitored by reading the change in weight at half-hour intervals. The top of the filter funnel was fitted with a rubber stopper and a glass outlet which was connected to the top of the Mariotte bottle by flexible tubing. In this way, air saturated with water could move freely into the system from the top.

The cumulative outflow of water was collected in the plane of the membrane filter, and its volume was plotted against the square root of time, resulting in an approximate straight line. The slope of this line was divided by the filtration area. This was taken as the sorptivity, S, for these conditions (Sparrow 1978). When water loss from the sand-sludge sample slowed to less than 0.1 g/h, the sample was removed and the moisture ratio, V, of the sample (volume of water per unit volume of solids) was determined.

For those pressures above 0.2 bar (i.e., 0.33, 0.66 and 1.0 bars) the apparatus consisted of stainless steel soil permeability cells (capacity 125 ml, filtration area 2.1 cm^2) fitted with a membrane filter (0.45 µm-pore size, bubbling pressure 1.52 bars) presaturated with water. Seventy five millilitres of sand-sludge mixture were added to the cell and pressure was applied from a constant pressure gas supply ($\pm 6.9 \times 10^{-4}$ bar). Cumulative outflow of water was collected in the plane of the membrane filter and measured in relation to time. Sorptivity was calculated for each pressure, as described above. The moisture ratio of the mixture in the filtration cell was measured when outflow ceased.

The sorptivity values and moisture ratios were plotted against all six moisture potentials (0.033, 0.066, 0.1, 0.33, 0.66, 1.0 bars) to obtain the drainage characteristics of the sand-sludge mixture. These were the sorptivity-moisture potential relationship and the moisture characteristic (water content-moisture potential relationship), respectively. The moisture potential is the potential which arises from the interaction of

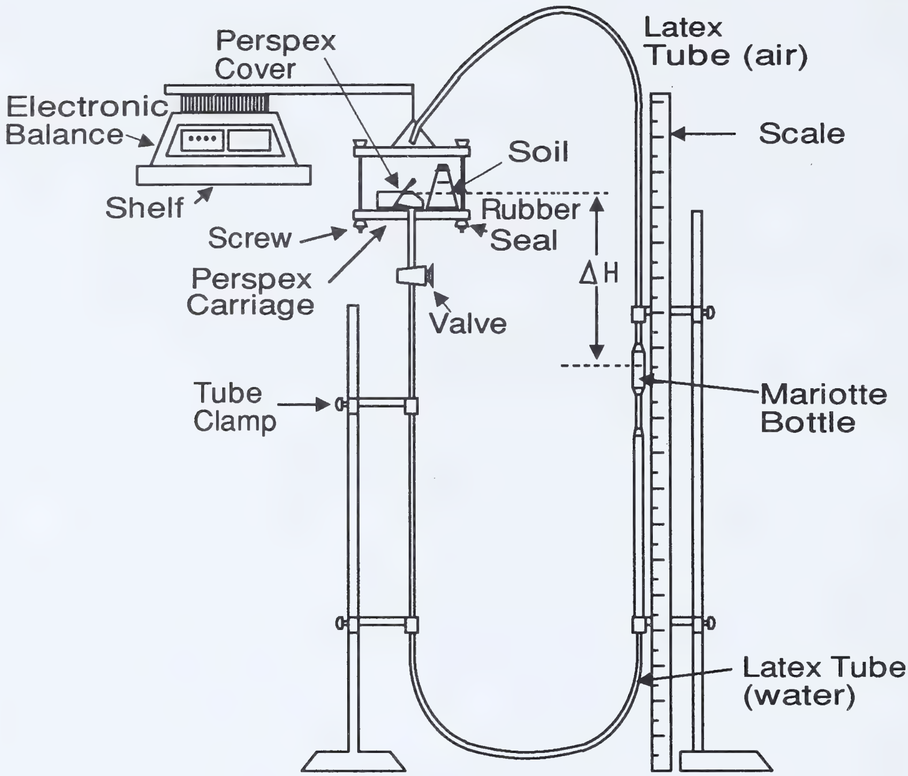

Figure 3. A schematic representation of a modified hanging balance.

water and the soil (the result of capillary and surface adsorption effects) and is the moisture-retaining potential which has to be overcome to dewater the sand-sludge mixture. For the constant-pressure filtration experiments, the moisture potential was the negative value of the applied pressure. The overburden potential, often considered at pressures below 0.01 bars, was not included (Smiles 1974).

3.1.2 Results

The relationship of moisture ratio to moisture potential in a 3:1 sand-sludge mixture with 1,000 ppm lime ($Ca(OH)_2$) is shown in Figure 4. The solids content of the mixture--another measure of moisture content--is also shown on the abscissa. Moisture

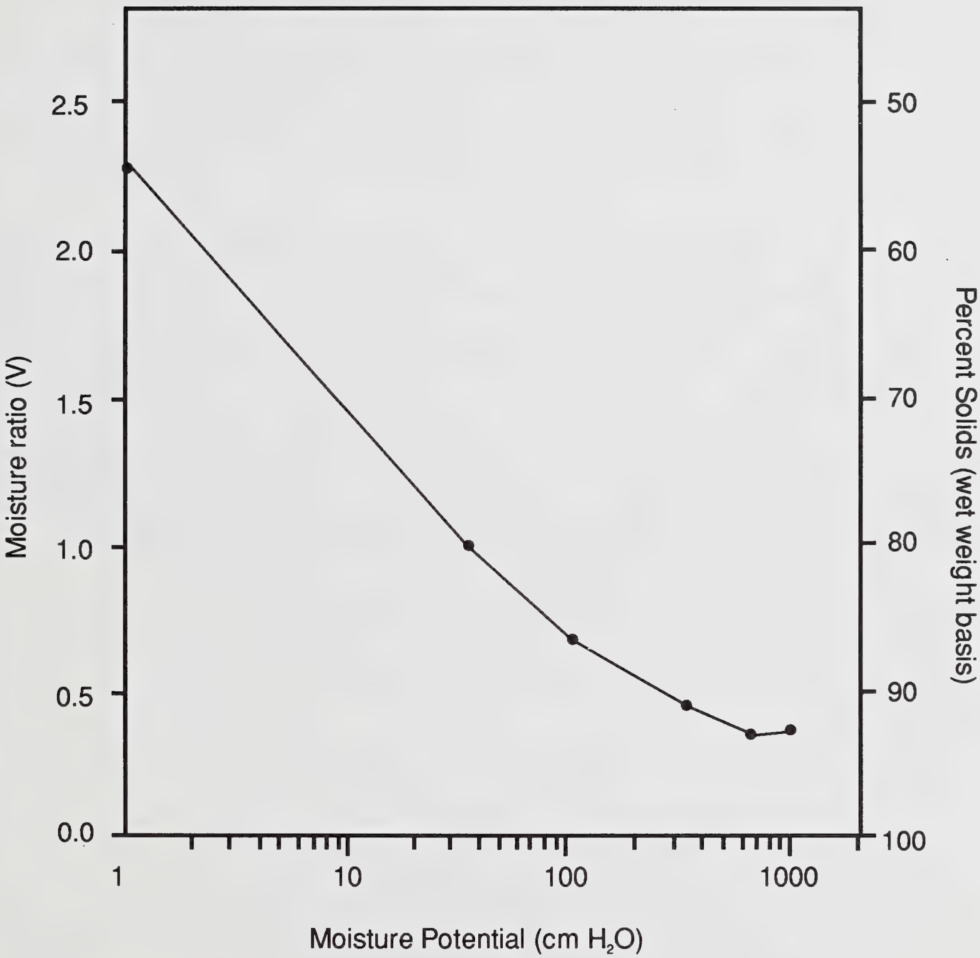

Figure 4. Moisture characteristic curve of a 3:1 sand-sludge mixture amended with 1,000 ppm lime.

potential is shown as centimetres water instead of bars or kilopascals (1,020 cm = 1 bar = 100 kPa) to facilitate later calculations of drainage and evaporation (Sparrow 1978).

A 3:1 sand-sludge mixture drained to a moisture ratio of 0.6 or 88% solids (wet weight basis) with as little as 0.1 bar suction pressure.

The sorptivity of the sand-sludge mixture increased almost linearly with increasing moisture potential (Figure 5). Between 0 and 0.1 bar, sorptivity increased from approximately 0.15 to 0.25 cm/ $\sqrt{h}$. At 1.0 bar moisture potential, sorptivity was about 0.46 cm/ $\sqrt{h}$.

From Figures 4 and 5 it was possible to calculate: (1) the equilibrium solids line (or the final depth of the consolidated sand-sludge after dewatering); (2) the average moisture in the profile after drainage; and (3) the time it took to dewater sand-sludge mixtures.

3.1.2.1 Initial conditions. Consider a suspension of sand-sludge and water with a uniform initial moisture ratio, Vn, (volume of water per unit volume of solids):

$$Vn = \frac{\gamma c(100-s)}{\gamma w \; s} \qquad \textit{(Equation 5)}$$

where

γc = specific gravity of solids (2.65 g/cm^3)

s = solids content of mixture (%)

γw = specific gravity of water (1 g/cm^3)

The sand-sludge suspension with an initial moisture ratio, Vn, is ponded on a sand bed to a depth, Tn. (Note the general situation represented in Figure 6).

The volume of solids per unit area, M, is given by:

$$M = \frac{Tn}{(Vn + 1)} \qquad \textit{(Equation 6)}$$

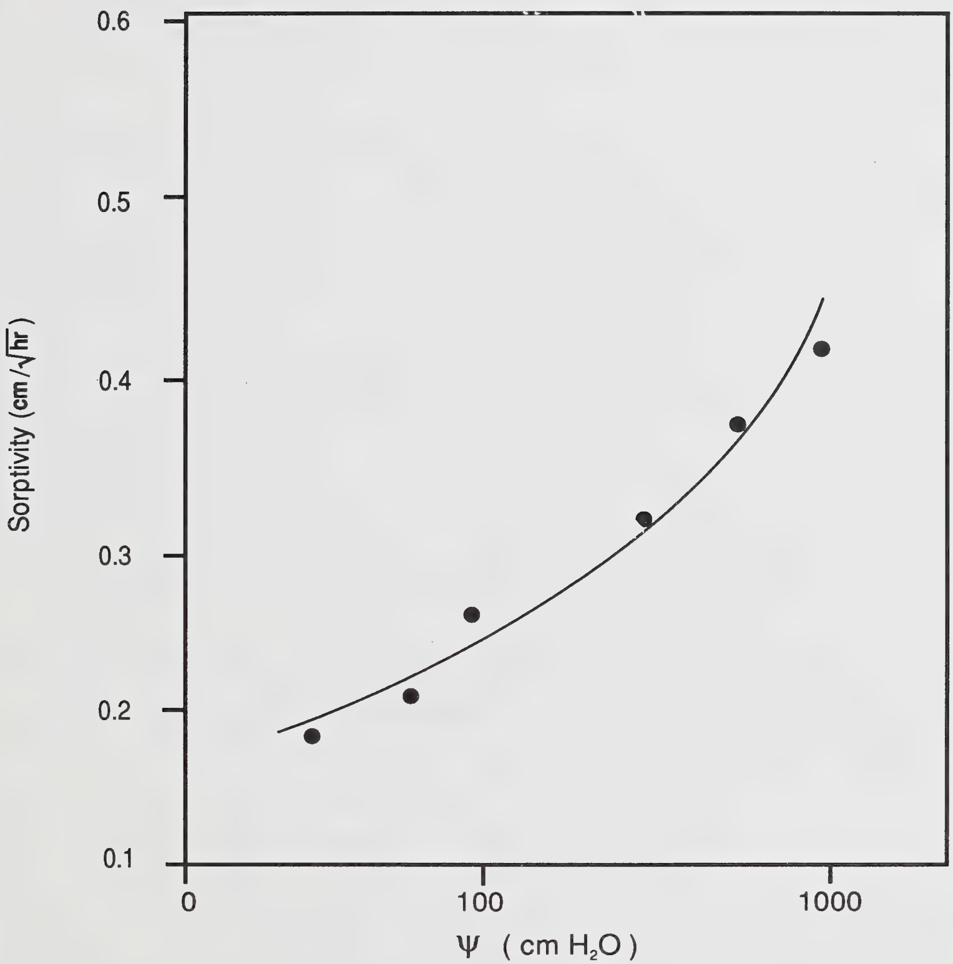

Figure 5. Sorptivity-moisture potential relationship of 55% solids, 3:1 sand-sludge mixture amended with lime.

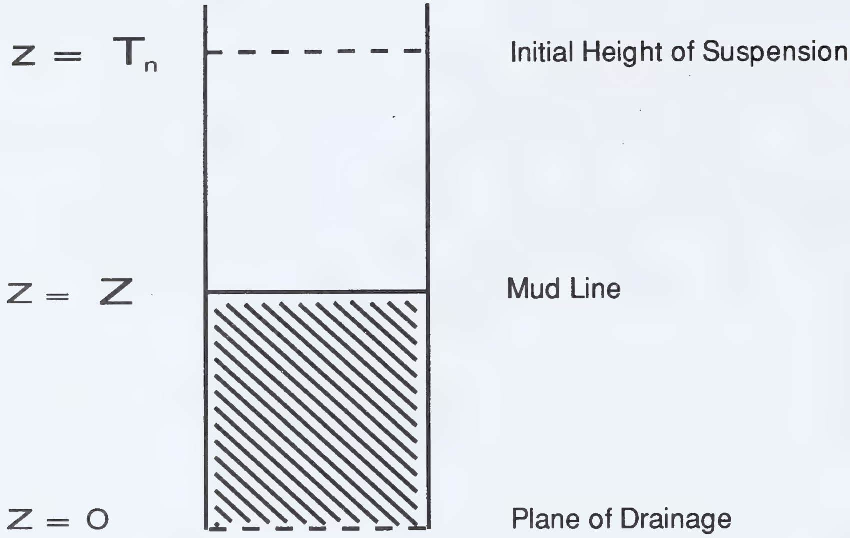

Figure 6. Representation of sludge undergoing drainage and consolidation.

3.1.2.2 Final depth of consolidated mix after dewatering. The total height of the sediment at equilibrium, Z, is related to corresponding moisture potentials at the top and bottom of the sediment by (Sparrow 1978):

$$Z = \int_{\Psi O}^{\Psi Z} \left(\frac{V+1}{\gamma c - 1} \right) d\Psi \qquad \textit{(Equation 7)}$$

where:

Ψz = moisture potential at top of sediment (cm H_2O)

Ψo = moisture potential at bottom of sediment (cm H_2O)

V = moisture ratio (dimensionless)

γc = specific gravity of the solids (taken as 2.65 g/cm^3).

For conditions of free drainage (i.e., the free water surface is maintained in the plane of the bottom of the sediment), values of Ψo and Ψz can be shown to be -Z

and -Z-M(γc-1), respectively. Therefore, under free drainage, Equation 7 can be rewritten as:

$$Z = \int_{-Z-M(\gamma c-1)}^{-Z} \left(\frac{V+1}{\gamma c-1}\right) d\Psi \qquad (\textit{Equation } 8)$$

Z is the equilibrium position of the mud line after drainage.

The calculation is carried out by approximating the moisture characteristic curve (Figure 4) over the integration range (or the segment of interest) and choosing the moisture ratio at the middle of the range, ($\bar{V}$), i.e., at:

$$\Psi = -Z-\frac{M}{2}\,(\gamma c-1) \qquad (\textit{Equation } 9)$$

Then:

$$Z = (\bar{V} + 1)M \qquad (\textit{Equation } 10)$$

where

Z = height of sediment at equilibrium (cm)

$\bar{V}$ = moisture ratio at the middle of range of interest (dimensionless)

M = volume of solids per unit area (cm^3/cm^2)

Since Z is present in the limits of integration, it is calculated by trial and error:

1. Choose a value for Z (estimate the level of the mixture after dewatering);
2. Determine the value of $\bar{V}$ at the middle of the corresponding moisture potential range, where

$$\Psi = -Z-\frac{M}{2}\,(\gamma c-1);$$

and

3. Calculate $Z = (\bar{V} + 1) M$

And repeat these steps until Equation 10 is satisfied.

3.1.2.3 Average moisture in profile after drainage. This is the moisture ratio at the middle of the range of interest, $\bar{V}$, and has already been calculated when Equation 10 is satisfied. The moisture ratio can also be read as percent solids (Figure 4).

3.1.2.4 Dewatering times. The dewatering equation was described in Section 3.1.1 (page 18, Equation 4) and consisted of a drainage component ($S\sqrt{t}$) and an evaporation component (E).

If we begin with a mixture at 55% solids and dewater to 80% solids on a drained bed during five summer months (May to September) in Fort McMurray, and assume or calculate the following:

1. The specific gravity of the mixture is 2.65 g/cm^3, then Vn (original moisture ratio), then from Equation 5 =

$$2.65 \times \frac{(100-55)}{55} = 2.17$$

Vo (final moisture ratio) =

$$2.65 \frac{(100-80)}{80} = 0.66$$

2. The ponding depth (Tn) to be 50 cm, then from Equation 6:

$$M = \frac{50}{(2.17+1)} = 15.8\ cm$$

and i_T (total water to be lost) = M (Vn - Vo)

i_T = 15.8 (2.17 - 0.66) = 23.9 cm;

3. For the initial conditions, the appropriate moisture potential, Ψ, for selecting the sorptivity (S) value is given by (Sparrow 1981):

$$\Psi = \frac{-Tn}{\gamma w}\left(\frac{\gamma c + Vn\gamma w}{Vn+1}\right) \qquad \textit{(Equation 11)}$$

where

Tn = ponding depth (cm)

γc = specific gravity of solids (2.65 g/cm^3)

γw = specific gravity of water (1 g/cm^3)

Vn = initial moisture ratio (dimensionless)

for Tn = 50 cm

$$\Psi = -50\left(\frac{2.65 + 2.17}{2.17 + 1}\right) = -76.03\ cm\ H_2O$$

from Figure 3: S (at Ψ = -76.03) = 0.235 cm/$\sqrt{h}$;

4. For five summer months in Fort McMurray, Alberta, a conservative estimate of class A pan evaporation is 6.5 cm/mo or E = 0.01 cm/h. With these values for S and E, the equation $i = S\sqrt{t} + E$ is evaluated for i_T as shown in Table 5.

In the first 20 days, evaporation plays a lesser role than drainage in dewatering. However, by the end of the first month, more water is being lost through evaporation than through drainage. By the end of the second month, when dewatering to 80% solids is nearly complete, cumulative evaporative losses are almost double those resulting from drainage.

There are two reasons for the low amount of water loss by drainage. First, the sorptivity (a value related to the hydraulic conductivity of the mixture) is low (0.235 cm/$\sqrt{h}$). Second, total drainage is a function of the square root of time. Therefore, increasing the time has a minimal effect on the cumulative drainage.

Table 5. Calculation of dewatering time from 50% to 80% solids for a 3:1 sand-sludge mixture (50-cm depth) at Fort McMurray.

Time h	Time days	Drainage ($S\sqrt{t}$) (cm)	Evaporation (cm)	Total (i_T) (cm)
240	10	3.64	2.4	6.04
480	20	5.15	4.8	9.95
720	30	6.30	7.2	13.50
960	40	7.28	9.6	16.88
1200	50	8.14	12.0	20.14
1440	60	8.92	14.4	23.32*

* Desired i_T to obtain 80% solids was calculated at 23.9; therefore dewatering is complete after 60 days.

Also, it can be shown by using Equation 10, ($Z = (\bar{V} + 1)M$ that the equilibrium solids line of a sand-sludge mixture 50-cm deep and dewatered to 80% solids is 29 cm. In other words, 42% of the original volume is lost as 23.3 cm of water is removed. The average moisture ratio in the profile ($\bar{V}$) after dewatering is 0.82 (or 86% solids, wet weight basis).

When the initial ponding depth is deeper, e.g., 200 cm, sorptivity increases to 0.33 cm/h owing to the increased hydraulic head. The amount of water that must be lost to achieve 80% solids becomes:

$$i_T = M\,(Vn - Vo)$$

$$= 63.09\,(2.17 - 0.66) = 95.27 \text{ cm}$$

The equilibrium solids line is 95 cm. There is a 52% consolidation in volume through dewatering. The average moisture ratio of the dewatered profile is 0.51 (91% solids, wet weight basis). The effect of increasing depth on dewatering time is shown in Table 6.

Table 6. Calculation of dewatering time from 50% to 80% solids for a 3:1 sand-sludge mixture (2-m depth) at Fort McMurray.

Time		Summer years	Drainage ($S\sqrt{t}$) (cm)	Evaporation (cm)	Total (i_T) (cm)
h	months				
720	1	<1	8.85	7.20	16.0
3600	5	1	19.8	36.0†	55.8
7200	10	2	28.0	36.0†	64.0
36000	50	10	62.6	36.0†	98.6*

† Assumes that after one summer, evaporation ceased owing to surface crusting.
* Desired i_T at 80% solids is 95.3; therefore dewatering is complete just before the end of the 10th summer.

By comparison, it takes 25 times longer to dewater 200 cm of sand-sludge than to dewater 50 cm. Drainage exceeds evaporation only in the first month; by the end of the first summer (5 months), evaporative losses are almost twice the drainage losses. After one summer, however, the evaporation losses are assumed to be negligible owing to the formation of a surface crust. Nine more years are needed to dewater completely 2 m of sand-sludge where drainage is the only dewatering mechanism.

3.1.3 Discussion

Constant-pressure filter tests using the methods outlined by G.J. Sparrow and colleagues (Ihle et al. 1983; Sparrow 1978; Sparrow 1981; Sparrow and Ihle 1978) have proved extremely valuable in characterizing the drainage characteristics of sand-sludge mixtures. The relationship of moisture potential to moisture ratio provides a precise description of the moisture characteristic curve for dewatering sands and clays (Figure 4). Further, the sorptivity-moisture potential curve (Figure 5) provides a means for predicting the effect of any factor (overburden surcharge, hydraulic head, flocculent amendment, changing ratios of sand and sludge, etc.) on the drainability, consolidation, and final solids content of the proposed mixture.

Dewatering lime-amended, sand-sludge mixtures by drainage and evaporation is simple and predictable, if the original pooling depth of the mixture is kept shallow (less than 1 m). However, the area required to dewater 25 x 10^6 m^3 sludge per year, using these assumptions, would exceed 2,500 hectares (6,000 acres). The dewatered product at 80% solids would be stable (> 100 kPa strength) and would occupy approximately one-half the volume of the original ponding depth (that is, there will be approximately 50% consolidation). Therefore, a new layer could be added on top each year if drainage were installed. The very conservative values used for evaporation in this calculation (6.5 cm per month in the summer) means that the system is secure, regardless of changing meteorological conditions.

Sand-sludge mixtures can be poured to any depth and dewatered using drainage and evaporation. However, the dewatering time increases exponentially with the thickness of the layer (Table 7). Secondary problems of drainage water disposal over centuries and a continual subsidence of the surface owing to gradual dewatering make this scheme unattractive.

3.2 EFFECT OF CALCIUM AMENDMENTS ON SAND-SLUDGE MIXTURES

Chemical amendments to enhance the dewatering of oil sands sludge have been commonly proposed. The highly dispersed state of colloids after bitumen extraction causes relatively slow settling and troublesome consolidation (Scott et al. 1985). The clays are dispersed owing to their geological origin (Erskine 1982) and the sodium hydroxide used in the extraction process.

Calcium hydroxide, or quick lime, has been recommended to prevent the segregation of sand and fines (Scott et al. 1985). At a 3:1 ratio of sand to fines, the optimum concentration of lime was 1,000 parts per million (dry weight solids), but the recommendation varied according to the solids content of the mixture.

Table 7. Calculation of dewatering times for various 3:1 sand-sludge mixtures from 50% to 80% solids at Fort McMurray, Alberta.

Depth (m)	Sorptivity (cm/√h)	Drainage (cm)	Evaporation (cm)	Total water loss (cm)	Time (year)
1	0.28	15.2	32.4	47.6	1
10	0.53	443.5	32.5*	47.6	194
50	1.3+	2,348.5	32.5*	2381	906

* Assumes that evaporation ceases after 1 year owing to surface crusting.
+ Sorptivity value estimated by extrapolating Figure 4 to 7.6 bars (7,600 cm H_2O).

Since calcium additions will affect the relative balance of dispersion and aggregation in sand-sludge mixtures, the hydraulic properties could also be modified. A knowledge of the hydraulic properties is essential for predicting the extent and rate of dessication, whether the cause is evaporation, transpiration, internal drainage, or some combination of the three. Hydraulic conductivity is the measure of the amount of water passing through a cross-sectional area per unit of time (flux), relative to a change in hydraulic head over a change in distance (hydraulic gradient). Since the latter term--hydraulic gradient (H/L)--is the ratio of a length to a length, it is dimensionless. Therefore, the dimensions of hydraulic conductivity are the same as the dimensions of flux, namely, length per unit time (e.g., cm/day).

The objectives of these experiments were: (1) to determine the amount of $Ca(OH)_2$ needed to prevent segregation of 3:1 sand-sludge mixtures at various solids contents; and (2) to characterize the effect of calcium amendments on the hydraulic conductivity of sand-sludge mixtures.

3.2.1 Materials and Methods

Sand and sludge properties are described in Section 2. The 3:1 sand-sludge mixtures were prepared to yield three solids contents: 40%, 45%, and 50% (dry weight basis). The three mixtures were amended with $Ca(OH)_2$ at concentrations varying from 50 to 1,500 parts per million. They were thoroughly stirred and dispensed into 1 L glass cylinders (used in the measure of particle size distribution) and left undisturbed for 24 h. The mixtures were then inspected visually for evidence of segregation and probed with a metal rod to confirm separation of the sand and fines. Each treatment was replicated three times.

For purposes of measuring hydraulic conductivity, tailings sand and sludge were added in a 3:1 ratio and mixed with five amendments or left unamended as a control. The treatments were:

1. $Ca(OH)_2$ .... 300 ppm
2. $Ca(OH)_2$ .... 1,300 ppm
3. $CaCl_2$ .... 1,000 ppm
4. $CaSO_4$ .... 1,000 ppm
5. H_2SO_4 .... 300 ppm
6. Control

The solids content of all treatments and the control was adjusted to 54% by adding tap water. Each treatment mixture and the control was poured, in triplicate, into acrylic cylinders (6-cm diameter, 30-cm length) fitted with a filter paper and wire mesh screen over the drain outlet. Drainage was prevented by inserting a rubber plug. The cylinders were left undisturbed for 3 days to allow initial consolidation. The cylinders were then connected to a constant hydraulic head, the drainage plugs were removed, and leachate water was collected in volumetric cups with plastic lids to prevent evaporation. Hydraulic conductivity was measured for 37 days.

3.2.2 Results

There was a well-defined relationship between the solids content of sand-sludge mixtures, the amount of $Ca(OH)_2$ added, and the occurrence of segregation (Table 8). At both 40% and 45% solids, segregation of the sand and fines occurred at 200 ppm calcium hydroxide or less. At 50% solids, segregation did not occur at 250 ppm $Ca(OH)_2$; lower concentrations of calcium hydroxide were not tested at this solids content.

The concentration of amendment added to the sand-sludge mixture was a primary determinant of saturated hydraulic conductivity (Figure 7). All calcium amendments in excess of 1,000 ppm yielded a final conductivity that exceeded 0.3 cm/day; the sand-sludge mixture treated with calcium hydroxide at 1,300 ppm had the highest initial (1.85 cm/day) and final (0.84 cm/day) conductivities. However, when $Ca(OH)_2$ was added at only 300 ppm, initial and final conductivities were only 0.41 and 0.02 cm/day, respectively.

Even though the non-amended sand-sludge mixture (control) began with a relatively high conductivity (0.45 cm/day), it had fallen to an extremely low value (0.02 cm/day) after 37 days. The H_2SO_4 amended mix showed a similar pattern of behavior (Figure 7).

Only sand-sludge mixtures amended with $CaCl_2$ (1,000 ppm) or $CaSO_4$ (1,000 ppm) showed little change in conductivity over 37 days. The $CaCl_2$ averaged 0.68 cm/day and the $CaSO_4$ averaged 0.13 cm/day.

The total amount of water leached from the unamended 3:1 sand-sludge mixture over 37 days was 18.4 mL or 8.8% of the initial pore water (Table 9). Neither $Ca(OH)_2$ nor H_2SO_4 at 300 ppm increased significantly the total volume of water moving through the columns. But $CaSO_4$ and $CaCl_2$ at 1,000 ppm caused approximately a 100% increase over the control, and $Ca(OH)_2$ at 1,300 ppm yielded a 900% increase. In the case of the high concentration of $Ca(OH)_2$, four-fifths of the initial pore water was replaced in 37 days (Table 9). However, as can be seen from Figure 7, a great part of the increased flow owing to 1,300 ppm of $Ca(OH)_2$ took place in the first 5 days.

Table 8. The effect of solids content and $Ca(OH)_2$ on the segregation of 3:1 sand-sludge mixtures.

Solids content (%)	Concentration of $Ca(OH)_2$ (ppm)								
	50	100	200	250	375	500	750	1,000	1,500
40	S[1]	S	S	[2]-	NS[3]	-	NS	-	NS
45	S	S	S	NS	-	NS	-	NS	-
50	-	-	-	NS	-	NS	-	NS	-

[1]S = segregating mixture
[2]- = no measurement made
[3]NS = non-segregating mixture

3.2.3 Discussion

Sand-sludge mixtures need calcium amendments to prevent segregation. The amount and form of amendment has been recommended by Scott et al. (1985), but segregation of sand from fines often occurs in laboratory and field trials even when these recommendations are followed closely. (See Section 4.3 for examples in the field; there were also unreported experimental units in the laboratory trials discussed in this section that segregated in spite of an optimal ratio of sand and sludge being provided and the addition of recommended levels of lime). Sometimes as little as 250 ppm $Ca(OH)_2$ was sufficient to keep sand in suspension with the colloidal clays, even at high (50%) solids content.

The hydraulic conductivity of an unamended 3:1 sand-sludge mixture was very low: 0.02 cm/day after equilibrium was reached. By adding 1,300 ppm $Ca(OH)_2$ the hydraulic conductivity was increased to 0.84 cm/day, a 40-fold increase.

As a basis for comparison, Table 10 gives values of hydraulic conductivity for 3:1 sand-sludge mixtures and other soil and geological materials found in Alberta. The subsoil is 100 times more water-permeable than the unamended sand-sludge, even though it has 42% clay, whereas the sand-sludge mixture has less than 10% clay.

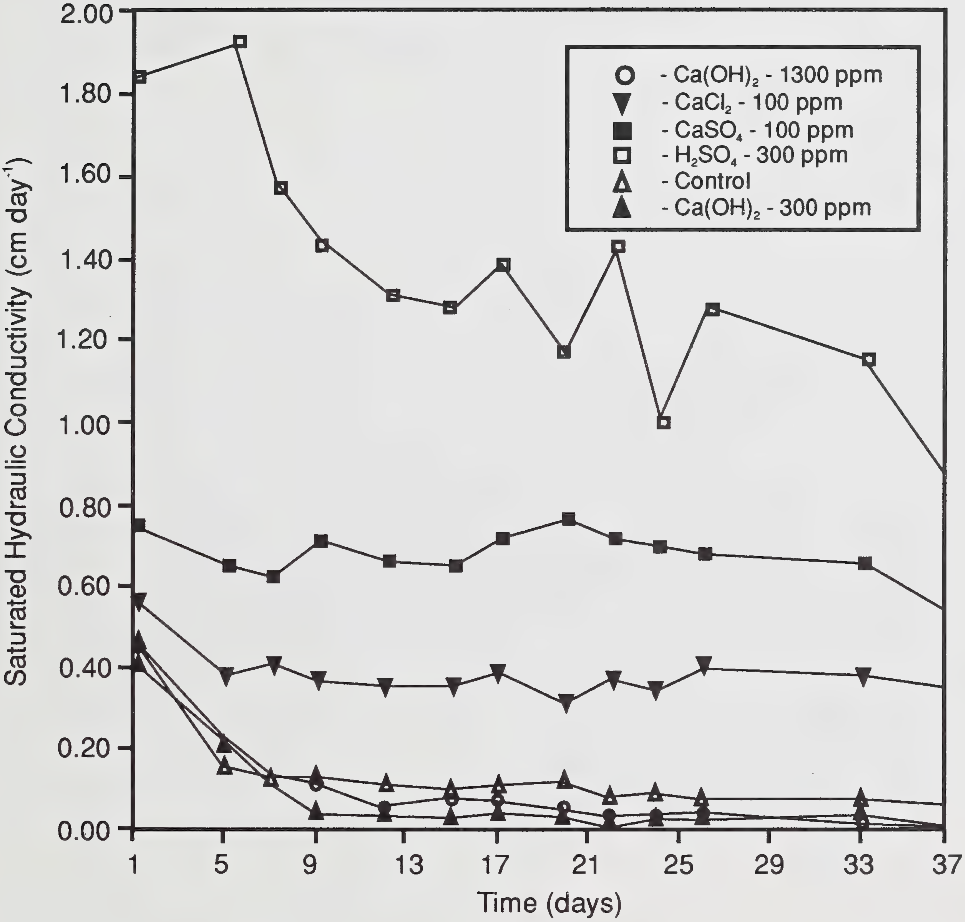

Figure 7. Saturated hydraulic conductivities of amended and non-amended 3:1 sand-sludge mixtures over 37 days.

Table 9. The effect of amendments on the replacement of water in sand-sludge mixtures over 37 days.

Treatment	Total water leached[1] (mL)	Initial pore water replaced[2] (%)
Control	18.4	8.8
$Ca(OH)_2$ (300 ppm)	16.1	7.0
H_2SO_4 (300 ppm)	25.0	12.0
$CaSO_4$ (1,000 ppm)	59.4	28.0
$CaCl_2$ (1,000 ppm)	75.6	36.0
$Ca(OH)_2$ (1,300 ppm)	167.2	80.2

[1] Average of 3 replicates
[2] Porosity = 1 - (Bulk density/Particle density)
= 1 - (1.55/2.65) = 41.5%

Table 10. Saturated hydraulic conductivity values of various soil and geological samples originating from mining and agricultural operations in Alberta.

Sample type	Saturated hydraulic conductivity[1] (cm/day)
3:1 sand:sludge, unamended	0.02
3:1 sand:sludge, 1,300 ppm $Ca(OH)_2$	0.84
3:1 sand:sludge, 1,000 ppm $CaSO_4$	0.36
Malmo subsoil[2]	2.40
Sandstone[3]	121.00
Bentonitic shale[4]	0.08

[1] All hydraulic conductivities were measured using the same procedure in the same laboratory (Johnson 1985).
[2] An Eluviated Black Chernozem subsoil containing 25% sand, 37% silt, 42% clay, SAR = 11.
[3] An unweathered minespoil with 76% sand, 15% silt and 9% clay, SAR = 21.
[4] An unweathered minespoil with 32% sand, 34% silt and 34% clay, SAR = 35.

Sandstone has about the same proportions of sand, silt, and clay as in the oil sands mixture, but its hydraulic conductivity is 5,000 times higher than the unamended sand-sludge and 200 times higher than the mixture amended with 1,300 ppm of $Ca(OH)_2$. Only the bentonitic shale, an extremely sodic, high clay-content material found in thin layers throughout Alberta, is comparable to the sand-sludge mixtures in hydraulic conductivity.

The sand-sludge mixtures, formed from materials from which bitumen has been extracted with sodium hydroxide, did not conduct water, not even at moderate rates. Vertical drainage and the rates of water transmission to root systems growing in these materials would be very slow.

The use of high rates ($\approx$1,000 ppm) of calcium-based amendments, including $Ca(OH)_2$ and $CaSO_4$, increased the rates of hydraulic conductivity to levels slightly lower than those found in subsoils across the province. At concentrations of 1,000 ppm or more, the calcium amendments also inhibited the segregation of sand and fines in the mixtures.

Calcium chloride was more effective than calcium sulphate in increasing and maintaining hydraulic conductivity in sand-sludge mixtures owing to its higher solubility. Under standard temperature and pressure, only 1.7 meq of $CaSO_4$ dissolves per 100 g water; under the same conditions, 4.5 meq of $CaCl_2$ dissolves per 100 g of water. Although the sand-sludge contents affect the absolute values of solubility of each compound, their relative position does not change.

4.0 THE BIOLOGICAL DEWATERING OF OIL SAND-SLUDGE MIXTURES

Water is lost from soils to the atmosphere through the physical process of evaporation and the biological process of transpiration.

Evaporative losses from deep soils can be so small that it is impractical to dry material, such as tailings slurries and sludges, by purely evaporative means. Bare soil saturated with water loses water initially at the same rate as a free water surface; however, the rate of evaporation decreases rapidly as the soil surface begins to dry (Figure 8).

Plants provide a continuous pathway from the soil through the roots, stems, and leaves to an evaporating surface within the leaves where water is lost to the atmosphere. This constitutes the basis for biological dewatering. The soil-plant-atmosphere pathway, unlike unvegetated, dry soil, has a low resistance to water movement and water loss. The understanding and manipulation of biological dewatering is evident in prairie agriculture, where land is kept fallow to retain more moisture for a crop in the following year (Stewart 1984).

There is a great range in the transpiration rates of plants. This variability allows a wide choice of plant species for dewatering. However, most of the published literature has been concerned with the ability of plants to conserve water in agricultural situations (water-use efficiency to combat drought), rather than to test the ability of plants to consume large amounts of water. Furthermore, relatively few non-agricultural species have been evaluated for any aspect of transpiration or water loss.

Actual water loss from soil is usually less than the "potential" evapotranspiration--the amount of water that could be transferred from the soil to the atmosphere--because there are losses of energy from the system by reflection and radiation. The amount of shortwave radiation lost to reflection is about 25% for agricultural crops and between 15% and 60% for bare soils, depending on soil colour and wetness, both of which affect the reflective properties (Monteith 1973).

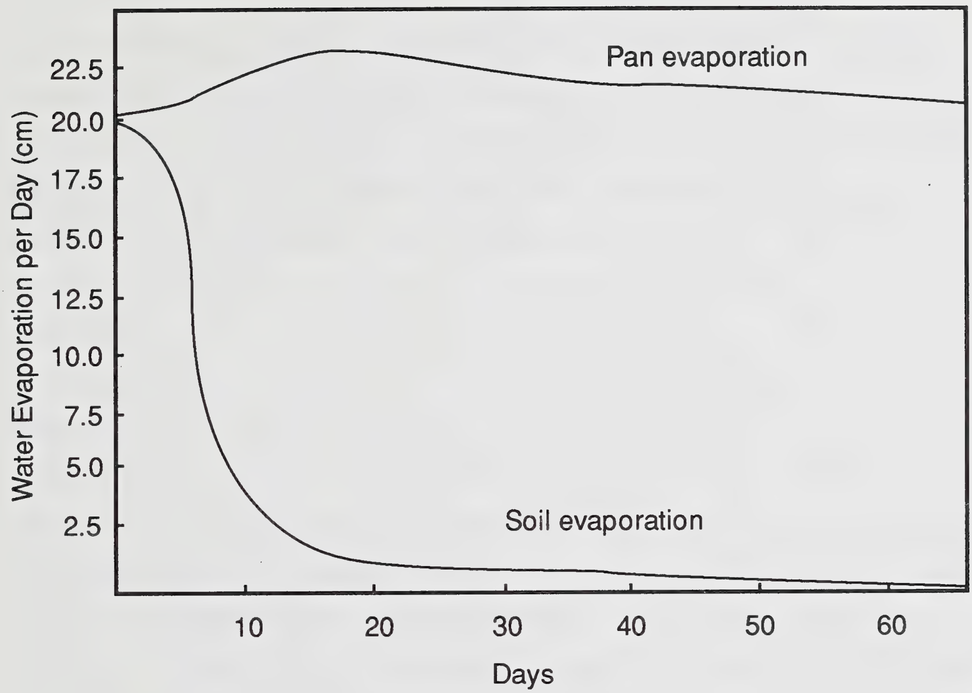

Figure 8. Comparison of evaporation from bare soil to a free water surface. Source: Cary and Evans 1974.

The climatic conditions of the Fort McMurray area pose particular problems for biological dewatering. At a latitude of 56° 44'N, Fort McMurray has a short growing season. There are 69 frost-free days from mid-June to August 25, with a mean annual temperature of -0.5°C, and a growing season mean temperature of 12.8°C. The mean annual precipitation (1951 to 1977) is 488 mm, including 140 mm of snow. Potential evapotranspiration rates average 500 mm/year (Monenco Consultants Limited 1983). The water balance--the difference between gain through precipitation and loss through evapotranspiration and drainage--is nearly zero.

Oil sands sludge, taken from the tailings pond at 20% to 30% solids, can be mixed with tailings sand or frozen and thawed to raise the solids content to approximately 50% (see Section 5). At 50% solids, the consistency is still custard-like,

and surface strengths are less than 1 kPa, incapable of supporting any weight. If enough water is removed to increase the solids content to 80%, sufficient shear strength will develop to support machinery, animals, humans, or overburden loads.

One cubic metre of sand-sludge mixture or pure sludge at 50% solids contains 730 mm of water. This means that 438 mm of water must be removed from the original 730 mm in order to dry the mixture or pure sludge to 80% solids. In the case of the sand-sludge mixture, approximately 110 mm of water leaves the mixture in the first few days as "expressed water", rising to the surface during preliminary consolidation. Therefore, biological dewatering must remove another 300 mm to 400 mm in the following 90 days. If approximately 500 mm can be potentially lost as a result of evapotranspiration, about 100 cm to 150 cm of sand-sludge mixture or sludge (initially 50% solids, finally 80% solids) could be dewatered in one summer. These calculations assume that surface water is drained off immediately and does not contribute to a negative water balance. If water collects on the surface--from rain or "expressed" from below during consolidation--dewatering will be difficult, even over long periods of time. Dewatering under conditions of surface water stagnation is impossible in 3 months.

A wide range of plants is available for use in biological dewatering. Because potentially large areas need to be managed, seeds should be readily available from suppliers or grown in the area. The seeds should have a high viability and germinate quickly at low temperatures to get an early start when temperatures rise. Sprigs, cuttings, or small seedlings are also a possibility, but planting would be more difficult and special facilities would be required for plant production.

Once established, the plants should grow quickly, producing a high leaf-area index and a deep root system to draw water from beneath the dry surface layer. The leaves should be carried above the soil surface to prevent them from being covered with water or bitumen from the surface of the tailings. If the plant stools, new stems will be produced in the open areas between the original plants, providing a more continuous coverage.

Contrary to what is desirable in agricultural species, plants used for dewatering should not mature early. Plants which flower or set seed usually stop root production and direct their productivity into seed production. Other species begin to senesce or go into dormancy after they flower. This would significantly shorten the time of rapid transpiration and reduce their effectiveness in dewatering. Also, resistance to frost is desirable to allow establishment in spring (May) or expand the growing season into the fall.

Probably nutrients will have to be added to the sludge to promote plant growth. Nitrate nitrogen is highly soluble and susceptible to loss in drainage water. Ammonium nitrogen may be more useful than nitrate in cost-effective management of sludge. The moderately high pH of the tailings and the clay itself can render phosphorus, in particular, unavailable for plant use.

Salinity will be a problem if plant species with low salt tolerance are used. Sodium and calcium are the predominant cations, and chloride and sulphate are the important anions. All ion concentrations increase as water is lost from the sludge. The plants must be able to maintain a reasonable rate of transpiration even as solute concentration increases at the end of the dewatering period. The increase in solute concentration may be slow enough to allow the chosen plant species to adapt to the higher salt levels. Fertilizers must be added cautiously to prevent the total solute load from exceeding the salinity tolerance of the plants.

The following sections give details of experiments carried out on the more important aspects of biological dewatering of sand-sludge mixtures. Most of the experiments were carried out at the Alberta Environmental Centre in Vegreville, Alberta, with sludge and sand brought in from Syncrude Canada Ltd. at Mildred Lake. In 1986, field experiments at Mildred Lake itself were begun. In late 1986, the discovery that pure sludge could be dewatered from 30% to 50% solids by a single freeze-thaw cycle caused a major redirection of research effort. Thus, the more recent experiments on biological dewatering are reported upon in Section 6.0.

4.1 THE SELECTION OF PLANT SPECIES

There are two primary contributions that plants can make to the reclamation of oil sands sludges: evapotranspiration and surface stabilization. The first is related to total water use; the second is related to the root mass, especially in the upper 30 cm of soil. In addition, plant species must conform to other reclamation criteria (Harwood 1979): potential survival in the local climate; suitability to the soil conditions on the surface; rapid growth; soil conditioning capability; forage quality; and aesthetics.

Using these characteristics as the criteria for selection, a two-stage experimental program was formulated to identify the most suitable plant species for dewatering oil sands sludge. Stage 1 was a broad screening of all possible vegetation that might adapt itself to Fort McMurray in general, and the sand-sludge mixtures in particular. The most practical and complete guides to plant selection for critical environments on the Canadian prairies and in the northern boreal forests were consulted (Alberta Agriculture 1978; Best and Looman 1979; Smoliak et al. 1976; Watson et al. 1980). In addition, conversations with practising ecologists, botanists, plant breeders, and plant physiologists across western Canada and the United States led to further additions of plants to the list of potential species.

After the list had been completed, the species with available seeds or root stalks in Alberta were tested for germination and growth potential. The following section documents how this was done and what the results were.

Stage 2 of the plant selection process for dewatering sand-sludge mixtures was carried out under more controlled conditions and led to a final selection of only two plant species to be used in Fort McMurray. This process is documented in Section 4.2.

4.1.1 Materials and Methods

The seeds and root stalks of selected plants were gathered in Alberta, purchased from seed companies, or obtained from seed collections at the University of Alberta, or the Alberta Environmental Centre.

Seed germination was tested by placing 10 to 20 seeds in a Petri plate, kept moist with wet filter paper on the bottom, and placed in a seed germination cabinet kept in the dark and set at 15°C. The plates for each species were replicated to use the total amount of seed available, or 100 seeds per species, whichever was the least. The plates were checked daily for germination and moisture, and left to incubate for 4 weeks.

Root cuttings were divided into 2-cm sections, with a visible bud on each section. They were tested for viability under conditions similar to those for seed testing and also in water-saturated sand, sterilized topsoil saturated with water, and a mixture of sand and topsoil saturated with water. The germination and establishment rates were measured only in the media in which at least one plant sprouted.

Seeds of 21 species were chosen for testing in pots of sand and sludge (see species marked with a superscript 2 in Table 12). Another six species (see species marked with a superscript 3 in Table 12) were tested from either root stalk, or as whole plants set directly into the sand-sludge mixture. The root stalks were handled in the same way as the root material used to test viability, but planting was done directly into the sand-sludge mixture.

The experimental design was a randomized complete block experiment consisting of 27 plant species and two blank treatments in each of three blocks. Seeds were planted directly into 155-mm diameter pots containing sand-sludge mixtures. The seeding rate was adjusted according to seed size--those with largest seeds being planted at the lowest rate.

Pots were assigned to blocks on the basis of the initial amount of water standing on the sand-sludge surface. One block contained pots which had little water (0 mm to 3 mm); the other two blocks contained pots which had larger amounts of standing water (3 mm to 6 mm).

A grid system was used for planting seeds into the pots, but standing water caused the seeds to float to the edges. Seed distribution, as a result, was very poor. Seeds of Calamagrostis inexpansa and Juncus balticus were poured as evenly as possible over the surface. Seeds of Typha latifolia were so small that no attempt was made to

count or distribute a predetermined number of seeds. Instead, a very large number of seeds was spread over the surface of the pots.

A portable cement mixer was used to mix sand and sludge. The following proportions yielded approximately a 3:1 (sand:sludge) mixture:

- 1 part sand (approximately 94% solids)
- 1 part sludge (approximately 30% solids)
- 1,000 ppm $Ca(OH)_2$ (based on solids).

The mixture varied in consistency and viscosity from batch to batch. Some water collected on the surface of the pots as soon as the mixtures were poured, indicating that the sand was not kept completely in suspension.

Fertilizer application rates were: 504 ppm N (ammonium nitrate), 175 ppm P (superphosphate), and 238 ppm K (potassium sulphate). Fertilizer was added to the sand-sludge during the mixing process. Each pot held approximately 2.3 kg of mixture.

The day length and average daily temperature for May at Fort McMurray were simulated. Table 11 shows day length and average maximum-minimum temperatures from May to July.

One Conviron E15 growth chamber was used for each block. The lowest temperature achieved was 4.7°C. Lighting consisted of cool, white, full-spectrum, fluorescent and standard 60-watt incandescent bulbs. Light intensity at the surface of each pot (15 cm above the floor) was 32,280 lux.

The watering regime followed long-term precipitation records for May at Fort McMurray (Longley and Janz 1978): approximately 33 mm. Demineralized water was added in small increments after the first week.

4.1.2 Results

Germination varied from 0% to 99% (Table 12). Generally, the agricultural species had very high germination rates, and the native species were lower. However, many native plants also had extremely high germination rates. Weed species, like foxtail

Table 11. Environmental conditions from May to July at Fort McMurray, Alberta.

Month	Average day length[1]	Average maximum[2]	Average minimum[2]
May	16 h 30 min	16.3°C	1.7°C
June	17 h 42 min	20.7°C	6.2°C
July	17 h 4 min	23.4°C	9.1°C

[1] Calculations of day length based on data supplied by Atmospheric Environment Services, Environment Canada, 6325 - 103 St., Edmonton.
[2] Temperatures calculated from Longley and Janz (1978).

barley and lamb's-quarters, showed excellent germination rates. Several of the most promising species, as judged from their adaptation to aquatic environments, did not germinate at all (Scirpus, Typha, Carex), possibly because of specialized requirements (R. Hermesh, Alberta Environmental Centre personal communication).

The 49 species selected from the literature and in consultation with experts in ecology and agronomy were pared down to 24 species for testing in sand-sludge mixtures (these are marked with superscripts 2 or 3 in Table 12).

The only two species which emerged in the pot experiment using sand and sludge were Atriplex patula and Phalaris arundinacea. The former established itself from seed, but did not grow well later. Reed canary grass (Phalaris arundinacea) did not germinate from seed, but several plants did grow from sprigs (rhizomes) put into the sand-sludge mixtures. After the first 3 weeks, these plants also ceased growth.

One or two seeds of creeping red fescue and timothy germinated, but the plants quickly died.

4.1.3 Discussion

The germination of seeds under laboratory conditions using Petri plates and controlled environment chambers was not indicative of how they would perform in a sand-sludge mixture. The mixture formed a crust as it dried out, which created a physical

Table 12. Plant species considered for dewatering sand-sludge mixtures, their germination rates, and their relative performance under controlled environmental conditions.

Scientific name	Common name	Germination %	Propagule[1]
Agropyron dasystachyum	Northern wheatgrass	90	S
Agropyron elongatum	Tall wheatgrass	90	S
Agropyron repens[2,3]	Couchgrass	31	R
Agropyron smithii	Western wheatgrass	0	S
Agropyron trachycaulum[2]	Slender wheatgrass	95	S
Agrostis stolonifera[2,3]	Redtop	84	P
Atriplex patula[2]	Spreading atriplex	83	S
Avena sativa[2]	Oats	99	S
Beckmania syzigachne	Slough grass	88	S
Bromus inermis[3]	Smooth brome	100	P
Calamagrostis canadensis	Marsh reed grass	0	S
Calamagrostis inexpansa[2]	Northern reed grass	16	S
Carex aquatilus	Water sedge	0	S
Chenopodium album[2]	Lamb's-quarters	85	S
Dactylis glomerata[2]	Orchard grass	95	S
Deschampsia cespitosa[2,3]	Tufted hair grass	84	P
Distichlis stricta	Salt grass	75	S
Eleocharis palustris	Creeping spike-rush	20	S
Elymus angustus	Altai wild rye	95	S
Festuca elatior[3]	Meadow fescue	15	R
Festuca rubra[2]	Creeping red fescue	81	S
Festuca scabrella[2]	Rough fescue	37	S
Hordeum jubatum[2]	Foxtail barley	96	S

continued...

Table 12. Concluded

Scientific name	Common name	Germination %	Propagule[1]
Hordeum vulgare[2]	Barley	83	S
Juncus balticus[2]	Wire rush	27	S
Medicago sativa	Alfalfa	76	S
Melilotus officianalis[2]	Yellow sweet clover	85	S
Phalaris arundinacea[3]	Reed canary grass	43	R
Phleum pratense[2]	Timothy	96	S
Poa alpina[2]	Alpine blue grass	89	S
Poa compresa	Canada blue grass	95	S
Polygonum amphibium[2]	Water smartweed	90	S
Polygonum scabrum	Green knotweed	-	S
Rumex occidentalis[2]	Western dock	95	S
Scirpus paludosus	Prairie bulrush	5	S
Trifolium hybridum[2]	Alsike clover	85	S
Typha latifolia[2]	Common cattail	10	S

[1] Seed, S; root cutting, R; whole plant, P.
[2] Plants selected for further testing from seed.
[3] Plants selected for further testing from root cuttings (R) or whole plants (P).

impediment to the emerging plant. Further, the water-saturated, sand-sludge mixture may have been anaerobic and, thus, partially toxic to emerging seedlings.

The large variability in the consistency and viscosity of the sand-sludge mixtures pointed to a problem of material handling. In several cases, the sand settled out of the mixture, leaving a layer of water at the top of the pot. The seeds were often washed out of the mixture and left floating on the surface. There was little chance that they would then germinate and root into the mineral materials.

Although the selection of plants for the pot experiment was wide ranging--it included agronomic species adapted to wet, alkaline conditions, weeds with enormous reproductive potential, wildland aquatic species, and whole plants and root stalks--almost all the plants failed. This can be attributed to the lack of control of the sand-sludge mixture quality, but this is also likely to happen in the field on a larger scale. It appears that the use of plants to dewater these mixtures will depend on identifying species that can tolerate extremely adverse conditions characteristic of the oil sands sludge environment. Of particular interest will be a tolerance to high pH, water-logging, residual bitumen, and a short growing season.

4.2 THE BIOLOGICAL DEWATERING OF SAND-SLUDGE MIXTURES: GREENHOUSE EXPERIMENT

The use of plants to dewater a sand-sludge mixture was evaluated in an 11 week experiment by growing nine species in lysimeters in a greenhouse. The purpose of the experiment was to quantify the effect of plants on water loss from a sand-sludge mixture under uniform conditions.

4.2.1 Materials and Methods

A mixture containing 49.5% dyke sand (containing 7% fines), 34.0% tailings sludge (32% solids) and 16.5% tap water was made up in several batches using a 0.16-m^3 cement mixer. The final mixture had a solids content of 58%. During the mixing, calcium hydroxide was added at a level of 1,000 ppm (dry solids). Fertilizers were added as ammonium nitrate (34-0-0) to give the equivalent of 1,300 kg N/ha; superphosphate (0-20-0) to give 1,300 kg P_2O_5/ha; and potassium sulphate (0-0-50) to give 1,300 kg K_2O/ha. The lysimeters were filled to a depth of 80 cm. Some settling took place, the expressed water was siphoned off, and extra material was added to restore the level to 80 cm.

The lysimeters were installed in a greenhouse in Edmonton, Alberta. Lighting was supplemented with 1,000-watt incandescent lamps. Air temperature was

controlled somewhat by water-cooled fans, but it was not possible to duplicate Fort McMurray site conditions. The experimental period ran from March through May 1985.

The plant species were:

Avena sativa	oats
Calamagrostis inexpansa	northern reed grass
Dactylis glomerata	orchard grass
Festuca rubra	creeping red fescue
Medicago sativa	alfalfa
Phalaris arundinacea	reed canary grass
Phleum pratense	timothy
Rumex occidentalis	western dock
Trifolium hybridum	Alsike clover

The plants were started from seeds in root trainers and transplanted to the lysimeters 3 weeks after germination. Eighteen plants were placed in each lysimeter. Three replicate lysimeters were used with each plant species, and three lysimeters were left unplanted to act as controls. The lysimeters were laid out in a randomized complete block design in the greenhouse.

The lysimeters were constructed from 45-gallon drums lined with a plastic coating. They had a diameter of 56.8 cm and an overall height of 85.3 cm. Total water loss was measured by lifting the lysimeter with a hoist on to a platform scale with a digital readout and a resolution of 50 g. Aluminum tubes, 5 cm in diameter and 90 cm in height, were installed in the center of each lysimeter and were held in place with a three-arm clamp. These tubes were used for access by a neutron moisture probe to determine water content within the lysimeters.

Water was added weekly to each lysimeter to simulate the average amount of precipitation from June through July for the Fort McMurray area:

Simulated month	Weeks/month (water added)	Average precip. per month (mm)	Total water added (mm)
June	1	8.3	8.1
July	4	15.4	15.2
August	4	18.4	18.1

The experiment ran for 2 weeks before the first water was added because the sand-sludge mixture was releasing water to the surface after mixing. From week 9 to 11, the water added to each lysimeter planted to reed canary grass and western dock was tripled to prevent a loss of plant turgor. Water loss was measured weekly for 11 weeks by weighing the lysimeters.

At the end of the experiment, the leaf area was determined by: (1) using a LiCor LI-3000 portable leaf area meter to measure the area of a subsample of the leaves from a barrel; (2) counting the total number of leaves; and (3) multiplying the area of the subsample by the total number of leaves.

Shear strength of the mixture was measured at 7, 25, and 50 cm using a vane shear strength meter.

4.2.2 Results

As the sand-sludge mixture consolidated in the lysimeters, water was expressed to the surface where it was siphoned off and combined into one sample. Water from all the lysimeters was combined and analyzed:

pH	9.7
electrical conductivity	1.9 dS/m
ammonium	57.5 ppm
nitrate	111.0 ppm
phosphorus	0.1 ppm

potassium	108.0 ppm
sodium	273.0 ppm
calcium	73.0 ppm
magnesium	2.0 ppm
chloride	172.0 ppm
sulphate	155.0 ppm

The pH was extremely high, owing to the addition of lime to keep the sand and sludge from segregating and the use of caustic soda during the oil extraction process. The electrical conductivity, at nearly 2 dS/m, indicated a soluble salt level high enough to affect sensitive plant species. The major contributing cation to this salinity was sodium (273 ppm), another additive during the extraction process. The anionic components were balanced between chloride and sulphate.

The relatively high concentrations of ammonium, nitrate, and potassium were from the fertilizer, but the phosphorus was adsorbed or precipitated, and very little appeared in the soil solution.

Plant growth on the sludge-sand mixture was variable. Oats and alfalfa grew poorly and died before the end of the experiment. Fescue, orchard grass, and hybrid clover grew poorly and produced little new growth over the 11-week experiment. The measurements of plant growth are given in Table 13. Of the species examined, reed canary grass, western dock, northern reed grass, and timothy produced the greatest increase in biomass, while western dock and reed canary grass developed the largest leaf areas. Visible evidence of the superior top growth of the latter two plant species in the lysimeters is shown in Figure 9. They also produced the deepest root systems. Roots reached the bottom of the barrel and may have gone further if the containers had been deeper.

Table 13. Measurements of plant growth on sand-sludge mixtures in lysimeters after 11 weeks. (Measurements of shoot dry weight are the mean of 3 replicates).

Plant species	Shoot dry wt. (g)	Leaf area (dm^2)	Root depth (cm)
Reed canary grass	362.4 a[1]	2.20	>80
Western dock	236.5 b	4.91	>80
Northern reed grass	156.7 c	1.10	38-43
Timothy	142.6 c	1.67	30
Alsike clover	71.4 d	--[2]	15
Orchard grass	44.6 d	0.45	15
Creeping red fescue	41.6 de	0.11	15
Oats	5.2 e	dead	10
Alfalfa	4.1 e	dead	10

[1] Measurements followed by the same letter are not significantly different at the 5% level.
[2] Not measured.

Over the 11 weeks of the experiment, water was lost from the lysimeters through evapotranspiration or by evaporation alone in the case of the controls. The cumulative water loss from the lysimeters is shown in Figure 10. For the first 2 weeks, there was little difference in the rate of water loss. When the western dock and reed canary grass plants increased in size, their evapotranspiration rates increased over the controls and other species. The total amount of lost water, expressed in millimetres, is given in Table 14. As water was lost, the surface of the material in the lysimeters subsided; this is also shown in the same table.

Alsike clover, orchard grass, and fescue lost less water than the control. Because of their poor physiological state, they transpired little water, and the presence of the leaf cover on the surface of the material in the lysimeter reduced the evaporative losses.

As water was transpired or evaporated from the surface, a moisture gradient was established. The depth profiles of the moisture content in the lysimeters after 11 weeks are shown in Table 15. Only reed canary grass and western dock significantly lowered the moisture content of the sand-sludge mixture at a depth of 45 cm. At this depth, approximately equal to the bottom of the lysimeter for these species, moisture content was reduced to about 15% (dry weight basis), at which point, the western dock plants wilted (Figure 11). In six of the other treatments, including the control, no significant dewatering occurred at depths beyond 15 cm (Table 15). Most of the water lost in these cases was apparently through evaporation from the surface.

The strength of the sand-sludge mixture rose rapidly as the moisture content decreased. The shear strength of the material measured at three depths is given in Table 16. The higher shear strength of the sand-sludge mixtures planted to reed canary grass and western dock reflects the removal of a larger amount of water. The increased shear strength resulting from dewatering by these two species extended to a depth of more than 50 cm, which was the bottom of the lysimeters.

4.2.3. Discussion

Of the nine species examined, four (reed canary grass, western dock, northern reed grass and timothy) grew reasonably well on sand-sludge mixtures that had been amended with fertilizers. Of these, reed canary grass and western dock caused significantly more water loss than all other species. The amount of dewatering was closely linked to the growth and physiological condition of the plants. Many of the plants examined in this experiment did not grow well on the mixture, even though they were placed in the lysimeters as seedlings rather than as seeds. The poor performance of these species eliminated them from further study.

The close relationship of water content to shear strength can be seen by comparing the data in Table 15 with those in Table 16. As the water content dropped below 15% (dry weight basis), the shear strength increased to over 100 kPa. At 100 kPa

Figure 9. Reed canary grass and western dock growing in sand-sludge mixtures in lysimeters.

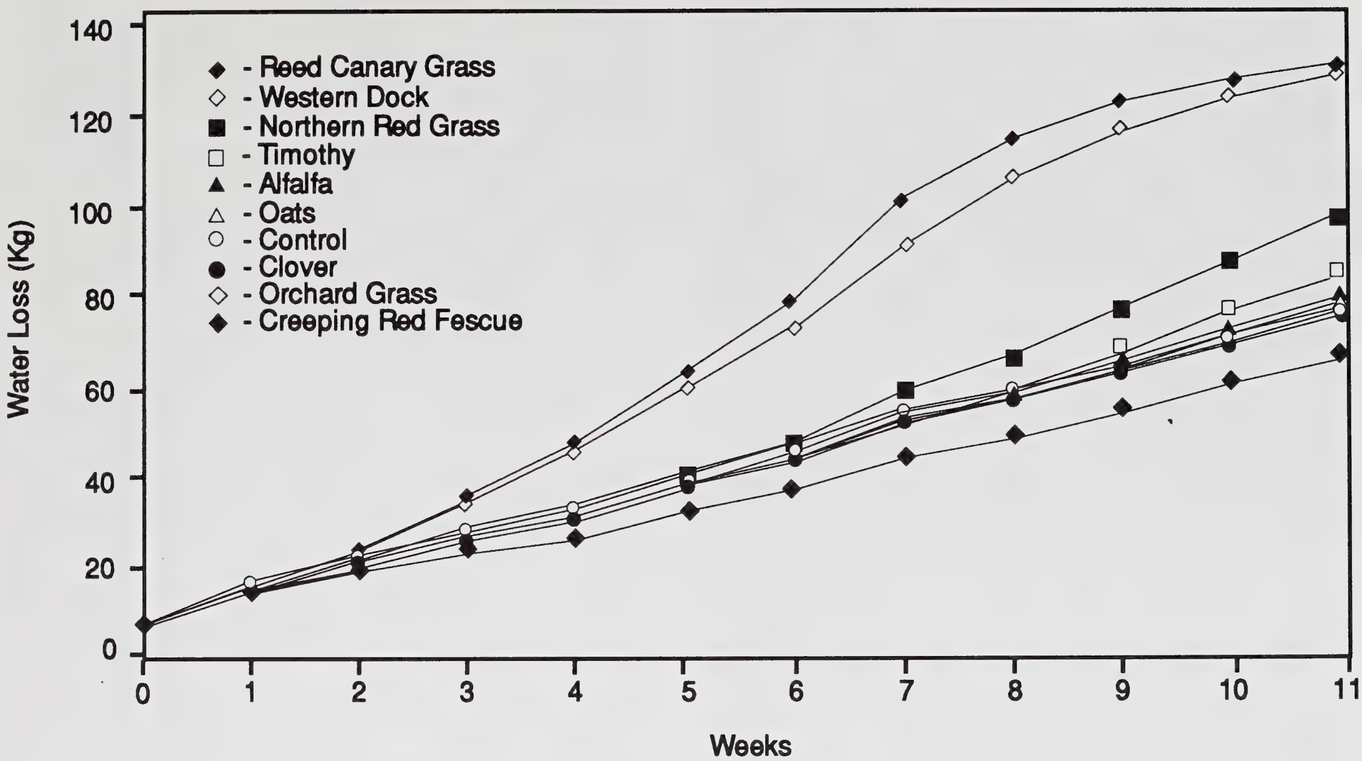

Figure 10. Cumulative water loss from nine plant species and an unplanted control on sand-sludge mixtures in greenhouse lysimeters.

Table 14. Total water loss and material subsidence in sand-sludge mixtures in lysimeters after 11 weeks of dewatering by plants. (Subsidence is the decrease in depth of the sand-sludge mixture due to water removal. Values given are the means of 3 replicates).

Treatment	Water loss and subsidence		
	Water lost (mm)	Subsidence (cm)	Subsidence (%)
Reed canary grass	542.0 a[1]	25 a	31
Western dock	536.1 a	24 a	30
Northern reed grass	408.1 b	23 a	29
Timothy	357.0 c	22 ab	28
Alfalfa	335.8 cd	20 bc	25
Oats	332.7 cd	20 bc	25
Control	323.7 d	19 c	24
Alsike clover	312.5 d	19 c	24
Orchard grass	309.4 de	18 c	23
Creeping red fescue	280.2 e	17 c	21

[1] Measurements followed by the same letter are not significantly different at the 5% level.

strength, sand-sludge mixtures can support loads of great weight (Shaw and Coward 1985); under field conditions, the sand-sludge surfaces could be reclaimed.

4.3 THE BIOLOGICAL DEWATERING OF SAND-SLUDGE MIXTURES: ON-SITE PIT EXPERIMENT

In May, 1986, a field trial was initiated on the Syncrude Canada Ltd. lease at Mildred Lake to determine the effectiveness of plants for dewatering sand-sludge mixtures under the climatic conditions of northeastern Alberta.

Figure 11. Western dock wilted after 11 weeks of growth in sand-sludge mixture.

4.3.1 Materials and Methods

The experiment was located northwest of the extraction and upgrading facilities in an area which had been cleared of vegetation and topsoil. Twelve pits, measuring 5 m^2 and 2.5-m deep, were excavated in the underlying lacustrine clay in early May. The soil forming the walls was extensively fractured and sloughing occurred as the walls dried out. Sand berms, approximately 0.25 m high, were placed around each pit to keep out surface runoff.

Tailings sand and sludge were supplied by Syncrude Canada Ltd. The previous year the sludge had been used in a dredging experiment, involving Clearwater shale removal. The sludge now contained a small percentage of solids and soluble salts originating from the Clearwater shale. The intention was to produce a mixture with a 3:1 sand-to-fines ratio having a solids content of at least 50%. Two concrete trucks were

Table 15. Final moisture contents (% dry weight basis) of sand-sludge mixtures in lysimeters after 11 weeks. (Measurements are the mean of three replicates.)

Treatment	Depth of moisture content reading (cm)		
	15	30	45
Reed canary grass	14.37 a[1]	15.73 a[1]	14.40 a[1]
Western dock	16.27 a	17.60 a	12.97 a
Northern reed grass	25.17 b	33.10 b	33.57 b
Timothy	28.73 bc	39.53 b	43.97 c
Alfalfa	33.63 cd	47.70 c	47.77 c
Oats	34.47 cde	49.13 c	46.50 c
Control	38.80 de	50.50 c	49.77 c
Alsike clover	39.30 de	51.20 c	48.40 c
Orchard grass	40.53 e	49.67 c	48.97 c
Creeping red fescue	48.37 f	48.97 c	50.90 c

[1] Measurements followed by the same letter are not significantly different at the 5% level.

used for mixing, each holding 6.5 m^3. Sand was placed with a backhoe in the revolving drum of the truck; the amount of sand was determined by counting the number of added bucket loads. Some variability occurred through spillage and incomplete filling of the bucket. The sludge was pumped from a holding pond into the cement truck drum to bring the total volume of the mixture to 6.5 m^3. Since this sludge contained approximately 18% solids (dry weight basis), it was not necessary to add water to achieve a 50% solids mixture. Lime was used to keep the sand and sludge fines from segregating, and fertilizers were added after weighing. Application rates were:

Lime ($Ca(OH)_2$)		13 kg/6.5 m^3
Ammonium nitrate	(34-0-0)	7.5 kg/6.5 m^3
Ammonium-phosphate	(11-51-0)	2.5 kg/6.5 m^3
Potassium chloride	(0-0-60)	1.25 kg/6.5 m^3

Table 16. Shear strength (kPa) of sand-sludge mixtures at 3 depths in lysimeter barrels after 11 weeks. (Measurements are the mean of 3 replicates).

Treatment	Depth of shear strength reading (cm)		
	7	25	50
Reed canary grass	133.0 a[1]	145.3 a	148.67 a
Western dock	116.7 a	101.33 b	97.00 b
Northern reed grass	79.7 b	13.30 c	1.07 c
Timothy	22.2 c	1.37 c	0.40 c
Alfalfa	1.9 c	0.33 c	0.13 c
Control	1.7 c	0.17 c	0.13 c
Oats	1.6 c	0.40 c	0.27 c
Orchard grass	1.2 c	0.23 c	0.17 c
Alsike clover	1.0 c	0.23 c	0.20 c
Creeping red fescue	0.5 c	0.17 c	0.13 c

[1] Measurements followed by the same letter are not significantly different at the 5% level.

Mixing was done continuously in the cement truck during load preparation and during the trip to the pit. Each batch took about 30 min to prepare. The density of the mixture was measured using a Marcy scale. Adjustments were made to the solids content of the mixture by varying the number of bucket loads of sand added to each batch. Approximately 100 loads were required to fill all 12 pits to a depth of 2 m. Filling took 5 days. After filling, 5.0-cm diameter aluminum pipes for neutron probe moisture measurements were installed in the centre of each pit.

Consolidation of the sand-sludge mixture began shortly after placement in the pits. As the material settled, a layer of clear water formed on the surface. The water was pumped out of the pits several times. The amount of water removed varied from 20 cm to nearly 1 m. The sand-sludge mixtures were sampled for solids content at several depths.

By June 5, consolidation had slowed, and the pits were seeded. A high seeding density was used in an attempt to get an adequate number of plants in each pit. Two pits were seeded with 100 g of reed canary grass (Phalaris arundinacea); two pits were seeded with 200 g of meadow foxtail (Alopecurus pratense); and two pits were seeded with 100 g of western dock (Rumex occidentalis). The seeds of the three plant species were separately mixed with peat and sprinkled on the pit surface. Reed canary grass and the meadow foxtail were purchased from a commercial seed supplier in Edmonton. Western dock seed was collected near Vegreville, Alberta, in the fall of 1985, from wild Rumex plants, cleaned, and tested for germination before May 1986. All three species had more than 95% germination. Three pits were left unseeded, and three pits were planted with seedlings of each species which had been grown in root trainers (Figure 12).

Several of the pits were flooded with water and tailings when an adjacent slurry pipeline ruptured twice on June 12 and 13. The pits were pumped out, and one pit was abandoned because of contamination from the slurry. Water continued to accumulate in the pits. It rained 13 mm from June 18 to 20, necessitating the removal of more water from the pits. On June 21, 4 to 12 cm of water had accumulated in the pits.

4.3.2 Results

Germination occurred in all pits, and seedlings could be seen floating in the slurry of peat and water. Reed canary grass seedlings grew to a length of approximately 25 mm.

The control over solids content and sand-fines ratio in the sand-sludge mixture was not good. The following example taken from one of the pits chosen at random shows a marked variation in solids from surface to bottom:

Depth	% Solids
50 cm	56.6
100 cm	60.4
160 cm	66.6

Figure 12. Reed canary grass plugs placed in sludge.

In addition, the presence of more than 30 cm (up to 100 cm in some pits) of clear water on the surface of the pits demonstrated an inability to control segregation. Earlier tests in the laboratory showed that non-segregating, sand-sludge mixtures would consolidate approximately 15% during the first 2 weeks after mixing and pouring. Those pits which had more than 30 cm of water overlying the mixture had undergone segregation rather than consolidation.

By June 26, reed canary grass seedlings were established around the edge of the pit where the water was shallow, but plants in the middle of the pit were flooded and died. Some western dock seedlings grew under water, but most of the germinated seedlings floated in the water. The transplanted western dock died quickly, except for

two plants which died about a month later. Floating seedlings did not root when the water was pumped out; most dried out and died.

The continual inflow of surface water into the pits made it almost impossible to establish plants. Also, the segregation of sand from the mixture caused several pits to drop in height. It was decided to combine the contents of the pits to bring the level of the mixture to ground level. On July 2, four pits were filled to the top and an additional 25 kg of lime were added to each pit as they were being stirred by the backhoe. Drainage channels, joining the filled pits to the emptied ones, were dug leaving a small clay barrier which could be lowered as the level of the full pits dropped. After draining overnight, three of the four pits were seeded and the fourth was left unseeded. By July 16, the pit surface was dry. Reed canary grass was 5-cm high and was growing abundantly around the edge of the pit. Western dock was starting to germinate, and some meadow foxtail plants were about 1-cm tall. At that time, establishment of all three species looked promising.

By August 13, all the reed canary grass plants on the newly seeded surface had dried. Plants, from 8 cm to 27-cm high, were growing around the edge of the pit on the wall material and in the drainage channel. Similarly, no meadow foxtail plants grew on the pit surface, but plants 5 cm to 8-cm tall were growing around the margins of the pit. A few western dock plants, at the four-leaf stage, were growing on the pit margins. Plants of all three species were growing in the walkways between the pits, in the drainage channels, and in low areas where seeds pumped out of the pits earlier had accumulated.

One original pit, which had not been drained since July, had 13 reed canary grass plants about 45-cm tall growing in more than 15 cm of water. These plants were growing near the edge of the pit, partly on wall material which had slumped into the pit.

The system of drainage channels effectively removed most of the rain water which fell on the pits, and the surfaces became firm. On August 13, three small areas on each recently drained pit were roughened and seeded with the three species. By August 20, none had germinated.

On August 25, the drainage pits had accumulated over 1 m of water and were pumped out. Three of four pits were reseeded to their original species. The fourth pit was left unseeded. At this time, none of the seeds planted on August 13 had germinated, and the first light frost of the season had occurred.

Observations for the season concluded on September 10. Some reed canary grass had germinated on the pit mixture, and a number of plants about 2 cm to 3-cm high were growing, primarily in the cracks. Meadow foxtail had sprouted as well, but no western dock plants were seen.

In September 1986, the site was protected from runoff by excavating a trench completely around the study site to channel the water away from the area.

4.3.3 Discussion

Plants could not be established on the surface of the pits because of the lack of surface drainage to control water accumulation resulting from consolidation and segregation. Frequent rains increased the amount of surface water and floated the seeds and seedlings off the surface of the sand-sludge mixtures in the pits. Many seeds were lost when the water was pumped out of the pits; some of these became established in the area around the site. The seedlings which remained in the pits were not conditioned to live out of water; they quickly dried out. Following the installation of the drainage channels, the pit surfaces became dry and firm and more conducive for establishing plants. Germination of seeds covered by the pit mixture did not take place until late in the summer; an inhibitory factor was investigated (Section 4.4).

4.4 FACTORS THAT INHIBIT PLANT GROWTH ON SAND-SLUDGE MIXTURES

The experiments at Fort McMurray using four species of plants on sand-sludge mixtures in field-scale plots (pits) were not successful for the following reasons: it was not possible to keep the sludge and sand in suspension, even with the addition of lime; the plots were constructed too close to a massive trial involving the movement of

sludge and overburden in pipelines which ruptured frequently and flooded the relatively small (5 m^2) plots; and there were no provisions in the beginning to handle surface drainage and, therefore, water from the mixture and rainfall collected on the surface. In addition to all of these reasons, a number of failed seeding trials with several plant species on these pits indicated some unknown inhibitory factor worked against the successful germination and establishment of plants on the surface of the sand-sludge mixtures.

Since there were a number of sources of potential inhibitors, it was decided to test them in a systematic way. A multi-factorial experiment was designed to test the effect of oil sand material in combination with lime and fertilizer on the germination and growth of reed canary grass.

4.4.1 Materials and Methods

Four kinds of sand-sludge mixtures might have affected plant growth: (1) the actual pit mixture used in the field experiment in the summer of 1986, consisting of sludge previously used to dredge overburden shales and sand; (2) Clearwater shale, the most prominent geological component of the previous dredged overburden, plus sand; (3) a new batch of dredge sludge, generated during the field season of 1986, plus sand; and (4) fresh sludge, pumped directly from the tailings pond in 1986 and not used during a dredging test, plus sand.

Each of these was transported to the Alberta Environmental Centre in Vegreville in the autumn of 1986 and used in a replicated experiment carried out in the greenhouse in February 1987. The previously unmixed slurry materials--Clearwater shale, dredge sludge and fresh sludge--were mixed with tailings sand in a 3:1 ratio (sand:shale or sludge). Enough water was added to bring the mixture to 55% solids (dry weight basis).

Two levels of fertilizer were used on each of these mixtures: no fertilizer was added to one-half and the same dose of nitrogen, phosphorus, and potassium (NPK) added to the mixture in the field was added to the other half, in the form of ammonium

nitrate (34-0-0), ammonium phosphate (11-51-0) and muriate of potash (0-0-60). The final concentrations of nutrient elements were:

nitrogen .... 830 ppm

phosphorus .... 386 ppm

potassium .... 378 ppm.

The mixtures were split again for two levels of lime addition: the low level of lime was 250 ppm, and the high level was 1,942 ppm.

The original pit mixture was used as a control because it had been amended with fertilizer and lime in the field the previous summer.

All mixtures, including the pit mixture, were stirred thoroughly in a 0.4 m^3 cement mixer with their respective amendments. They were then dispensed into clear plastic cups holding approximately 250 mL each. The mixtures in the cups were left to settle for 24 h, and the water collecting on the surface was removed by pipette. The sand settled out of the treatment, consisting of dredge sludge amended with 1,942 ppm of lime and no fertilizer. This treatment was then eliminated from the trial.

All experimental units were transported in boxes to Agriculture Canada's greenhouse facilities outside Vegreville. Fifteen seeds of reed canary grass were placed on the surface of each cup. The seeds were then covered with 0.3 cm of peat moss to keep the surfaces of the mixtures from drying. The experimental units were arranged in a completely randomized design on one table of the greenhouse.

Banks of overhead lights were installed to supplement the natural winter light and left on from 08:00 h to 17:00 h.

Daily observations were made on the number of germinating seeds and the progress of their establishment. The experiment ran for 35 days. At the end of the experiment the above-ground parts of the plants were harvested, dried, and weighed.

The mixtures were analyzed for ammonium-N, nitrate-N, and phosphorus. A saturated paste was prepared from each replicate to measure electrical conductivity (E.C.) and pH.

4.4.2 Results

Even though no fertilizer or lime had been added to the pit mixture for 9 months, it had high levels of nitrate-N and phosphorus and provided the best conditions for plant growth (Table 17). An average of 10 plants/pot germinated and established, producing an average of 140-mg dry matter/pot. The pit mixture had very low levels of ammonium-N (4.2 ppm), very high levels of phosphorus (178 ppm), and a relatively high level of soluble salts, with an electrical conductivity of 4.3 dS/m.

The Clearwater shale:sand mixtures that did not have fertilizer added performed nearly the same as the pit mixture. An average of more than 10 plants/pot produced 130-mg dry matter/pot. These mixtures had very low levels of both ammonium- and nitrate-N, little phosphorus (11.6 ppm) and very high levels of soluble salts (E.C. > 5.8 dS/m).

When fertilizer was added to the Clearwater shale:sand mixtures, all nutrient element levels increased dramatically, even though this was not reflected in higher values of electrical conductivity or pH. Plant germination decreased; only 1 plant/pot established on the low-lime treatment, and no plants survived the high-lime, fertilizer treatment. There was no harvestable biomass after 35 days on any Clearwater shale treatment with fertilizer.

The dredge sludge:sand mixtures showed much the same pattern as the Clearwater shale:sand mixture, although total biomass production per pot, even on the non-fertilized treatment, was low. Only 40 mg/pot was produced from 11 plants/pot. The addition of fertilizer with low or high levels of lime practically eliminated plant germination on these materials. The 1 plant/pot that did survive the addition of 250 ppm of lime produced a healthy 10 mg of biomass.

There was good seed germination and plant establishment on the fresh sludge:sand mixtures without fertilizer (10 plants/pot), but these plants only produced an average of 20-mg dry matter/pot, or 2 mg/plant. Nitrogen and phosphorus contents were low (<5 ppm), but not much lower than similar treatments on Clearwater shale:sand mixtures, where each plant produced 10 to 13-mg dry matter. When fertilizer was added

Table 17. The effect of oil sands material, fertilizer and lime on reed canary grass germination and growth. (Averages of 4 replicates except where noted.)

Material mixed with sand[1]	Fertilizer[2]	Lime[3]	Nutrients and soil properties					Plant response	
			NH_4-N (ppm)	NO_3-N (ppm)	P (ppm)	pH	E.C. (dS/cm)	Germ. (#/pot)	Biomass (mg/pot)
Pit mix	Added	High	4.2	273.8	178.0	8.5	4.3	10	140
Clearwater	None	Low	3.5	5.6	11.6	8.6	6.3	12	130
Shale	None	High	3.6	4.5	4.0	8.6	5.8	10	130
	Added	Low	203.3	110.0	121.1	8.3	7.3	1	0
	Added	High	78.1	7.3	78.8	8.4	5.7	0	0
Dredge	None[4]	Low	3.9	5.7	11.3	9.4	2.6	11	40
Sludge	None	High	--	--	--	--	--	--	--
	Added	Low	139.5	132.9	150.9	8.6	3.6	1	10
	Added	High	57.4	51.5	44.6	9.1	3.5	0	0
Fresh	None	Low	2.1	2.9	4.4	8.8	2.8	9	20
Sludge	None	High	2.1	3.4	2.0	9.2	3.5	10	20
	Added[5]	Low	59.9	5.5	59.3	8.8	4.2	3	10
	Added	High	54.8	45.1	70.8	9.1	3.9	0	0

[1] Sand was added at 3:1 ratio with other materials except pit mixture which already had sand added.
[2] Fertilizer when added was at 830 ppm N (NH_4+NO_3), 386 ppm P_2O_5, 378 ppm K_2O.
[3] Lime at low levels was 250 ppm and at high levels was 1,942 ppm.
[4] Only two replicates were used in these averages.
[5] Only three replicates were used in these averages.

to the fresh sludge:sand mixtures, the ammonium-N and phosphorus concentrations increased. The plant germination and biomass production dropped to nearly zero. Low-lime levels seemed to be marginally better than high-lime levels when fertilizer was added.

4.4.3 Discussion

Any inhibitory factors present in the pit mixture on the Syncrude Canada Ltd. lease near Fort McMurray were absent by the time the experiment was run in Vegreville the following winter. The pit mixture was used as a control to evaluate the potential of other combinations of oil sands sludge and dyke sand, and it gave the best response.

It is obvious from the measurements of germination and biomass production reported in Table 17 that the addition of fertilizer at the rates used in this experiment (N: 830 ppm; P_20_5: 385 ppm; K_2O: 378 ppm) caused a sharp decline in plant growth, regardless of the material mixture to which it was added. In fact, in almost all cases, fertilizer addition at this rate prevented germination and consequently eliminated plant biomass production.

When the nutrient levels and other associated soil properties (pH, electrical conductivity) were compared between treatments, the only factor common to all high-performing treatments was a low level of ammonium-nitrogen (NH_4-N). Beginning with the pit mixture in Table 17 and selecting out all responses that gave at least nine established plants after 35 days, the ammonium-N level never exceeded 4.2 ppm; whereas treatments showing very low seed germination and low biomass production were all associated with ammonium-N levels of >50 ppm.

There was no other soil property consistently associated with poor plant production in this experiment. Nitrate-N was low for most high performance treatments, but the pit mixture had extremely high levels of nitrate-N (273.8 ppm) and still produced more biomass than all other treatments. The same argument applied to phosphorus levels. The soil pH varied inconsistently, and some mixtures (Clearwater shale without fertilizer)

with extremely high electrical conductivity (>6 dS/m) resulted in high germination rates and high biomass production.

It is apparent that ammonium-N can cause establishment and growth problems for plants in a sludge environment. The ammonium that was present in the pit mixture when it was first used in Fort McMurray in the summer of 1986 was mostly gone by the time this experiment was conducted in February 1987. Consequently, plants grew well on material which had been extremely inhibitory until then. It is important to control ammonium-N levels in oil sands sludges that are being prepared for biological dewatering.

4.5 THE FERTILIZER REQUIREMENTS OF REED CANARY GRASS GROWN ON SAND-SLUDGE MIXTURES

The amount of nutrients present in either sludge or sand is small. An experiment was designed to determine the concentrations of nitrogen, phosphorus, and potassium adequate for the sustained growth of leaves and roots of reed canary grass.

4.5.1 Materials and Methods

Two hundred and eight kilograms of mixture was made by adding 131 kg of sand (4.6% fines and 7.6% water) to 96 kg of sludge (34.5% solids); 53 kg of water was added to give a 3:1 sand-sludge mixture with 55% solids. The mixture was stirred using an impeller on an electric drill. Nitrogen in the form of ammonium nitrate was added to the mixture to give 40, 80, or 120 parts per million (ppm) by weight. The nitrogen-containing mixture was dispensed into 12, 4.5-L pails, 20 cm in diameter. Each pail received 5.6 kg of sand-sludge mixture plus fertilizer. Phosphorus and potassium were added to each pail as monobasic potassium phosphate (KH_2PO_4) to give 20, 40, and 60 ppm phosphorus and 25, 50, and 75 ppm potassium by weight. The material in the pails was allowed to consolidate for several days, and the expressed water was decanted before planting.

Forty-eight pails were filled with all combinations of the four nitrogen and four phosphorus-potassium concentrations (including controls with no nitrogen and

phosphorus-potassium additions). Each nutrient combination was replicated three times. The pails were arranged evenly on the floor of a 4 m^2 growth chamber in a completely randomized design.

Reed canary grass was started from seed in root trainers filled with potting soil. When transplanted, the plants were 10 to 15-cm tall and well rooted. The plants, including the soil, were inserted into the fluid mixture in the pails. Each pail was transplanted with five reed canary grass plants which were trimmed to a height of 5 cm after planting. To lessen drying, a thin layer of peat was placed on the surface of each pail on the second day. The pails were re-randomized on day 37.

The growth chamber was set at 15°C (to reduce evaporation losses) and a 13-h light period. On the 18th day, the temperature was raised to 20°C to accelerate growth. The pails were watered when the water on the surface of the sand-sludge mixtures had disappeared.

Measurements of maximum plant height and tiller (shoot) number were made for each pail on days 23, 37, and 49. Eleven plants, one from each treatment having all 3 replicates with 5 plants each, were purposefully omitted from the last height measurement. Observations of plant condition were made at the time of measurement. Plants were cut off at the soil level on day 49, and the total leaf area of each pail was measured with a LiCor leaf area meter. The leaves and stems were dried in an oven at 80°C and weighed. Roots were washed and dried.

4.5.2 Results

The transplanted seedlings established well and began growing within a few days. Only 5 of the 240 plants died, probably from transplant shock.

Plants started at 5 cm, and by the time of the first measurement on day 23, there was a sizeable increase in height. Plant heights for the three observation dates are shown in Table 18.

Reed canary grass spreads by tillering, and the number of new tillers rapidly increased when nutrients were added. Nitrogen, phosphorus, and potassium were

required before a large increase in tiller number occurred (Table 19). By day 23, yellowing of the leaf tips was seen on some plants where no N, P, or K was added. A purple coloration of the leaves indicating phosphorus deficiency was seen on plants where P was not added. Plants with zero or low levels of nitrogen were noticeably less green than plants with higher (over 40 ppm) nitrogen levels.

The total leaf area of the plants in each pail at the time of harvest on day 49 is shown in Figure 13. Neither N, nor P and K alone, produced much new leaf area. With the addition of all three nutrients, leaf area markedly increased, nitrogen having a greater effect than the phosphorus-potassium combination.

A similar pattern of increase in total shoot weight is shown in Figure 14. If no nitrogen was added, there was virtually no increase in shoot weight regardless of the amount of phosphorus added. Similarly, if no phosphorus or potassium was added, higher doses of nitrogen (up to 120 ppm) had no effect on shoot weight. Approximately two times as much shoot weight was produced by plants having 120-40-50 ppm NPK than plants having 40-40-50.

The production of roots was improved by adding of N and the P-K combination, but the exact relationship between root mass and initial nutrient concentration was less clear (Figure 15). Any treatment including nitrogen, phosphorus, and potassium yielded more root biomass than those treatments without one of the nutrients. Beyond this, however, there were no significant differences between treatments insofar as their effect on root weight are concerned (data not shown).

4.5.3 Discussion

The additions of nitrogen and phosphorus increased the growth of shoots and roots in reed canary grass. Up to 120 ppm of nitrogen promoted shoot development, but higher concentrations did not increase root growth. Phosphorus and potassium additions were necessary, but relatively low concentrations produced optimal growth. Between 20 ppm and 50 ppm of each of these elements was adequate for good plant

Table 18. The effect of nutrient additions (N,P,K,) on the mean (n = 15)[1] height of reed canary grass plants grown in sand-sludge mixtures for 49 days.

Fertilizer treatment	Mean plant height on days after transplant		
N - P - K	Day 23	Day 37	Day 49
(ppm)		(cm)	
0-0-0	17.7	24.5	26.0
40-0-0	24.8	26.7	27.1
80-0-0	23.7	25.6	26.5
120-0-0	26.4	26.8	28.7
0-20-25	26.0	26.8	28.8
40-20-25	31.1	39.7	48.2
80-20-25	32.8	43.0	56.2
120-20-25	28.7	45.0	53.5
0-40-50	24.8	28.2	30.5
40-40-50	30.2	44.3	49.3
80-40-50	32.7	44.2	51.3
120-40-50	30.8	46.0	52.2
0-60-75	27.1	29.7	33.0
40-60-75	33.1	46.3	53.3
80-60-75	29.5	44.8	50.5
120-60-75	33.0	51.3	58.6

[1] Except for 5 of 16 treatments in which 1 plant died shortly after transplanting (n=14) and the last sampling date (Day 49) when n=14 for all treatments.

Table 19. The effect of nutrient additions (N,P,K) on the increase in mean (n = 15)[1] tiller number of individual reed canary grass plants grown on sand-sludge mixtures for 49 days.

Fertilizer treatment	Days after transplant		
N - P - K	Day 23	Day 37	Day 49
(ppm)		(cm)	
0-0-0	11.7	12.3	14.3
40-0-0	13.0	13.3	14.3
80-0-0	12.7	12.3	13.3
120-0-0	11.0	12.0	12.3
0-20-25	15.7	17.7	18.0
40-20-25	24.7	34.3	39.0
80-20-25	20.0	34.0	41.3
120-20-25	20.0	34.7	49.0
0-40-50	13.0	13.0	14.0
40-40-50	21.7	40.3	45.7
80-40-50	24.7	41.7	51.7
120-40-50	23.7	52.0	64.3
0-60-75	17.0	17.3	21.0
40-60-75	21.0	35.0	42.7
80-60-75	23.7	40.0	48.7
120-60-75	22.3	44.0	58.0

[1] Except for 5 of 16 treatments in which 1 plant died shortly after transplanting (n=14) and the last sampling date (Day 49) when n=14 for all treatments.

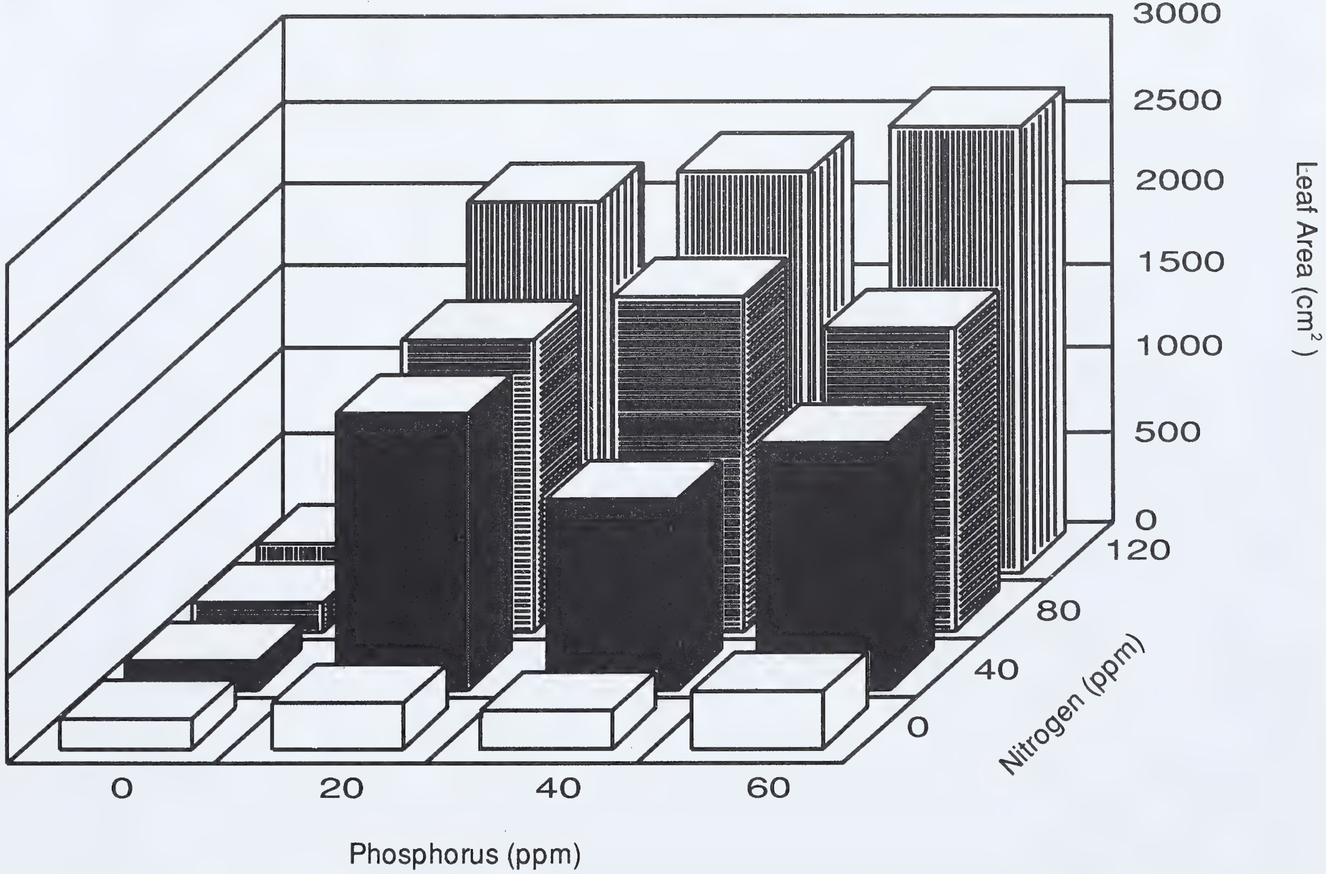

Figure 13. Mean (n = 3) leaf area (cm^2) of reed canary grass grown for 49 days in sand-sludge mixtures with varying nutrient (NPK) levels. (Each 20 ppm increase in P also includes a 25 ppm increase in potassium).

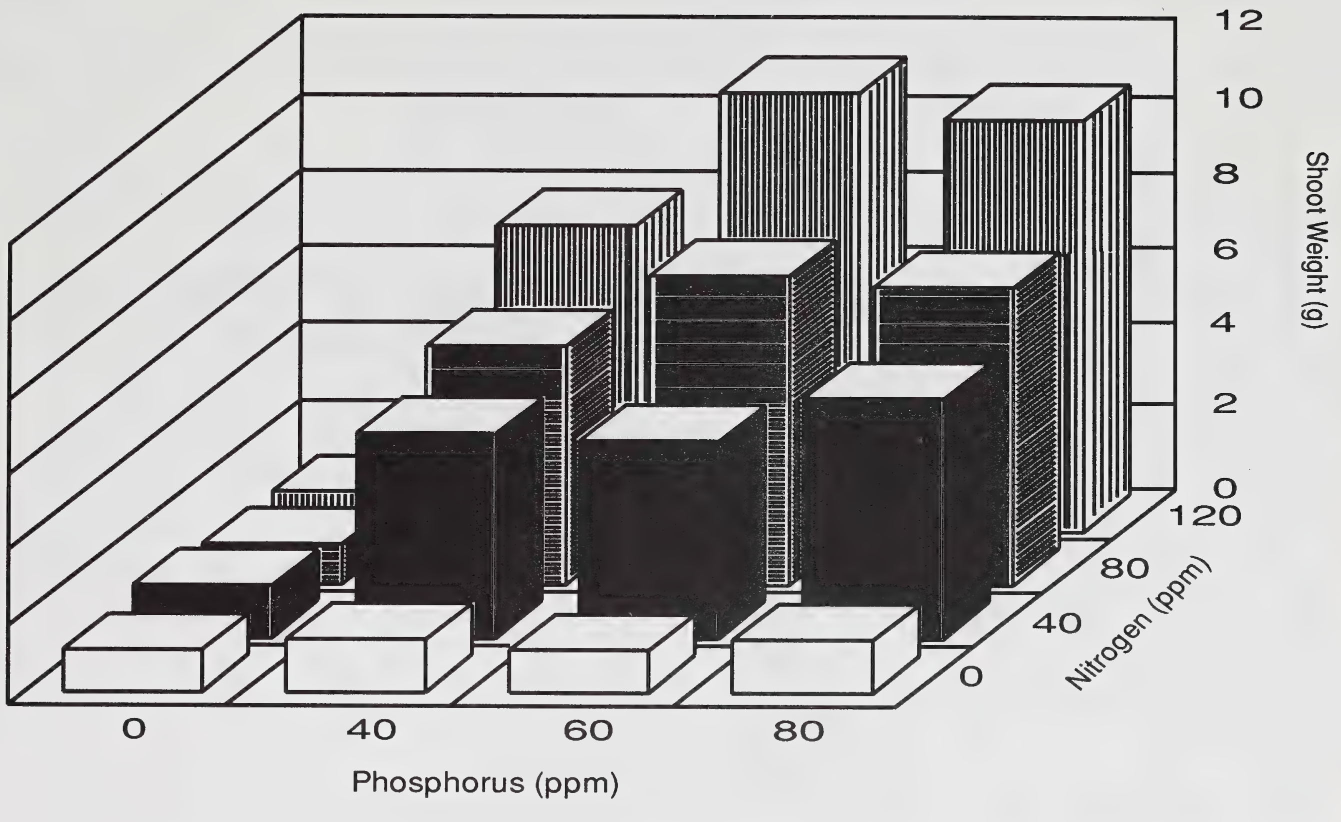

Figure 14. Mean (n = 3) shoot weights of reed canary grass grown for 49 days in sand-sludge mixtures with varying nutrient (NPK) levels. (Each 20 ppm increase in P also includes a 25 ppm increase in potassium).

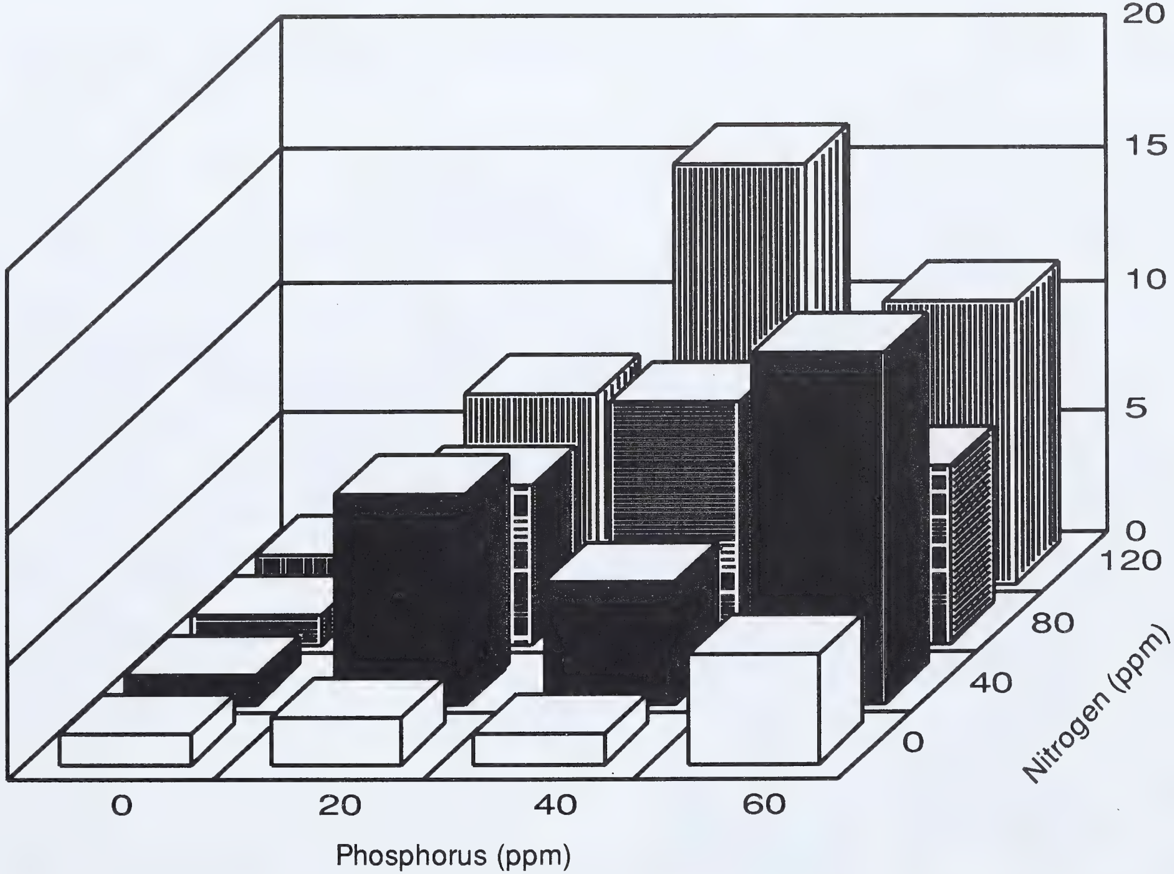

Figure 15. Mean (n = 3) root weights of reed canary grass grown for 49 days in sand-sludge mixtures with varying nutrient (NPK) levels. (Each 20 ppm increase in P also includes a 25 ppm increase in potassium).

growth. Adding either nitrogen or phosphorus-potassium alone did not bring about an increase in any plant growth parameter.

4.6 SEED GERMINATION ON SAND-SLUDGE MIXTURES

The success of biological dewatering of sand-sludge mixtures depends as much on plant establishment as on water use. Since extremely wet conditions prevail during the initial period of plant establishment, many of the most likely plant species are semi-aquatic and non-cultivated (i.e., native or non-agricultural). Very little information on seed germination of semi-aquatic species, including reed canary grass (Phalaris arundinacea) and meadow foxtail (Alopecurus spp.) used in wet agricultural fields, is available. A series of controlled germination experiments was carried out to identify the factors affecting the germination of semi-aquatic species, both agricultural and native.

4.6.1 Materials and Methods

Seeds were obtained from commercial seed suppliers in Edmonton, Alberta, or were collected from local plant populations in Vegreville and Fort McMurray in the autumn of 1986. The seeds of species from local populations were hand harvested and hand cleaned without scarifying or damaging the seed coat. Table 20 shows which species were used in each of four experiments.

4.6.1.1 Experiment I: Effect of temperature-light combinations. Fifty seeds of each species were placed on moist filter paper in disposable Petri plates. Germination tests were carried out in incubators with a provision for temperature control and light from fluorescent lamps. The four treatments consisted of: (1) 22°C-8 h light/16 h dark; (2) 22°C-24 h dark; (3) 15°C-8 h light/8°C-16 h dark; and (4) 15°C-8 h dark/8°C-16 h dark. Plates kept in the dark (2 and 4) were wrapped in aluminum foil. All treatments were replicated. Plates were kept for 32 days before ending the test.

4.6.1.2 Experiment II: Effect of temperature cycles. Fifty seeds of each of four species (Table 20) were placed on moist filter paper in disposable Petri plates. The plates were placed in controlled environment chambers set to cycle at (1) 8°C-16 h/1°C-8 h, (2) 15°C-16 h/9°C-8 h, (3) 25°C-16 h/10°C-8 h, or remain at (4) 9°C-24 h or (5) 19°C-24 h. During a 16 h period in each case, the controlled environment chambers were lighted by a mixture of fluorescent and incandescent bulbs (1,000 watts/m^2). The remaining 8 h of each cycle for each treatment were in darkness. The plates were examined daily, and the seeds which had germinated were counted and removed.

4.6.1.3 Experiment III: Effect of immersion in water and scarification. Seeds from nine plant species which might require high moisture or low oxygen conditions were scarified by scraping with a scalpel (Sagittaria cuneata and Zizania aquatica) or left intact (the remaining 7 species listed in Table 20, Experiment III). Fifty seeds of each species were placed in glass vials and filled with distilled water. The vials were kept in a controlled environment chamber at 25°C with continuous light for 45 days. Germinating seeds were removed weekly from each vial.

4.6.1.4 Experiment IV: Effect of mulches on seed germination on oil sands sludge. Seeds of Alopecurus pratensis, Elymus angustus, Phalaris arundinacea and Rumex occidentalis were: (1) placed on or just below the surface of a 3:1 sand-sludge mixture at 50% solids or (2) mixed with a mulch (chopped peat or commercial hydroseeding product made from wood fibre and a tackifier) and distributed on the surface of the sand-sludge mixture in a 1-cm layer. The 0.5 L volume pots were placed in a controlled environment chamber at 25°C with 16 h light and 8 h darkness. The pots were left in the chamber for 45 days.

Table 20. The assignment of plant species' seeds to various germination tests.

Plant species	Experiment			
	I (Light/ dark)	II (Temperature)	III (Water immersion)	IV (Mulches)
Alisma plantago-aquatica	†		†	
Alopecurus pratensis	†	†		†
Alopecurus arundinacea		†		
Beckmania syzigachne	†			
Carex aquatilis	†		†	
Deschampsia cespitosa	†			
Eleocharis palustris	†		†	
Elymus angustus	†			†
Glyceria grandis	†			
Hordeum jubatum	†			
Phalaris arundinacea	†	†		†
Rumex occidentalis	†	†		†
Sagittaria cuneata	†		†	
Scirpus paludosus			†	
Scirpus validus	†		†	
Typha latifolia	†		†	
Zizania aquatica	†		†	
Juncus balticus			†	

4.6.2 Results

4.6.2.1 Experiment I: Effect of temperature-light combinations. At 22°C and 8 h of light, seeds of four species germinated well (Table 21). Two of these species were native or wild (Rumex occidentalis and Hordeum jubatum) and two were agricultural grasses (Deschampsia cespitosa and Elymus angustus). Even though Phalaris arundinacea (reed canary grass) is an agricultural species with a high rate of germination in other tests under similar conditions, it only reached 37% germination in this instance. Alopecurus pratensis (meadow foxtail) germinated significantly better under dark than under light conditions (Table 21). Several native species, like Beckmania syzigachne, Carex aquatilis and Glyceria grandis showed low levels of germination under any of the four temperature-light combinations. Many native species, especially those from aquatic habitats, did not germinate at all under the conditions of this experiment.

4.6.2.2 Experiment II: Effect of temperature cycles. Of the four species tested for their ability to germinate in this experiment, only Rumex occidentalis, a native hydrophyte found throughout Alberta in wet areas, had 100% germination at all five temperature cycles (Figure 16). The other three plant species--common forage grass species for wet agricultural areas--had more than 50% and less than 90% of their seeds germinate at the highest temperature regimes (25-10, 15-9, and 19). However in all cases the commercial grass varieties performed poorly (<50% germination in 19 days) when ambient temperatures were less than 18°C. On the other hand, western dock (R. occidentalis), maintained its ability to germinate in spite of the low temperature, although it took 18 days for it to reach 100% germination at 8°C by day (under light) and 1°C at night (in the dark).

Western dock also showed little decrease in percent germination when seeds were left in storage for 1 year (Figure 16, upper 2 graphs). Only the low-temperature cycle (8°C-1°C) caused a delay in germination of one-year-old western dock

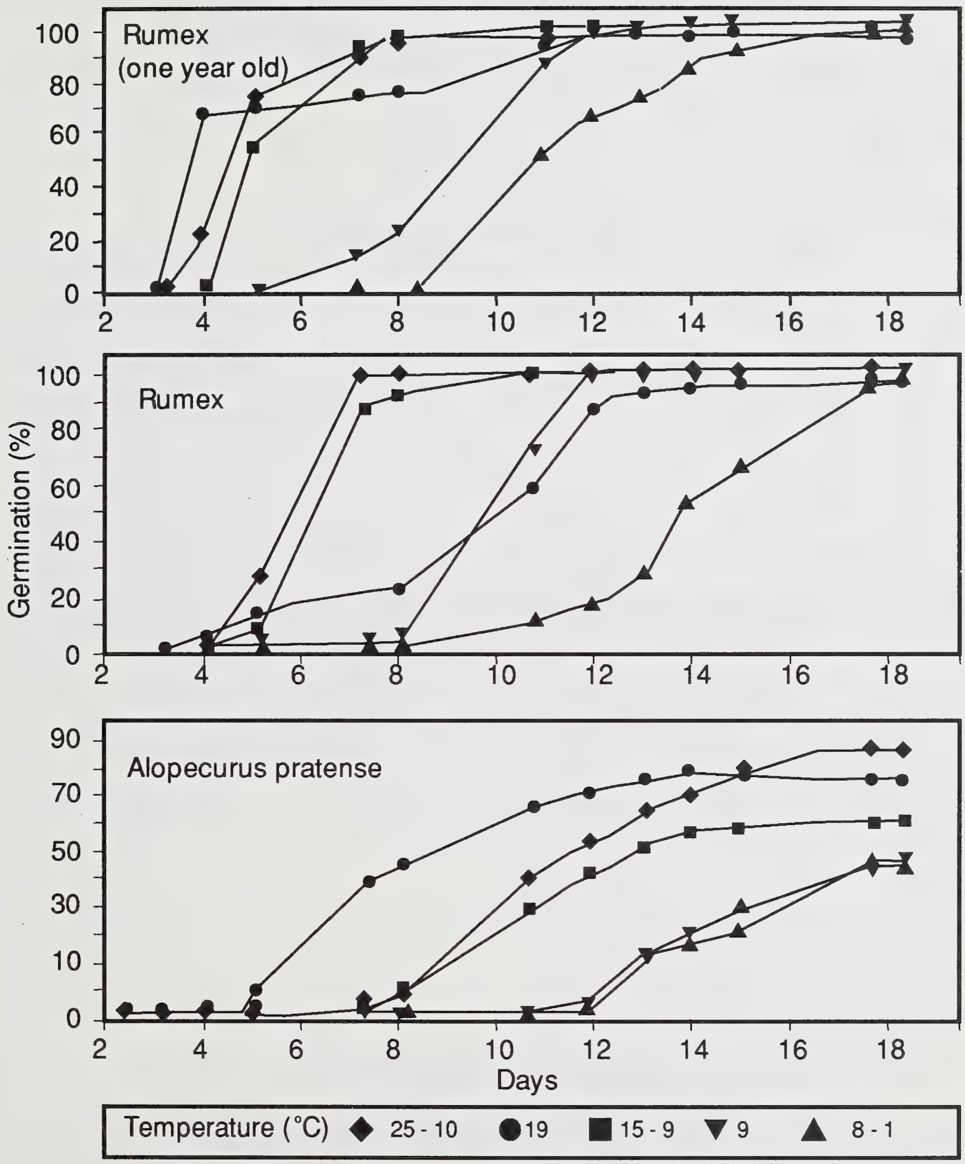

Figure 16a. The effect of temperature on the germination of various plant seeds.

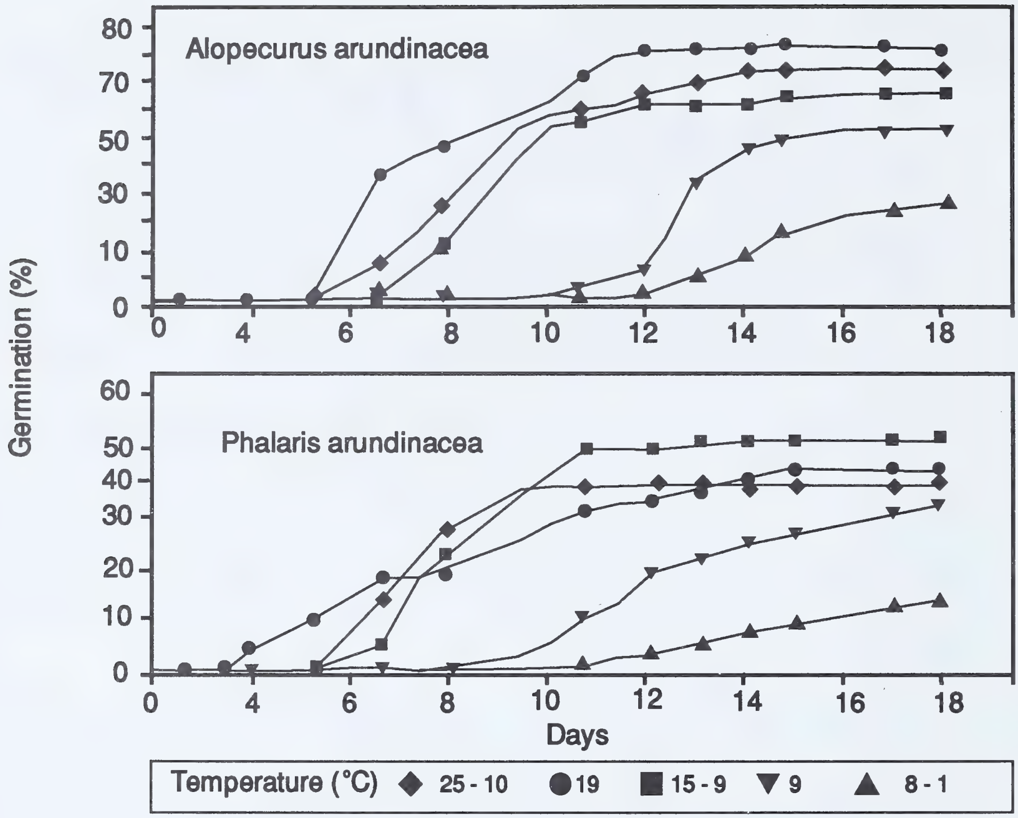

Figure 16b. The effect of temperature on the germination of various plant seeds.

seeds. Even in that case, the western dock seeds reached 100% germination after 19 days.

4.6.2.3 Experiment III: Effect of immersion in water and scarification. Complete immersion in water greatly improved the germination of Alisma plantago-aquatica, Juncus balticus, and Typha latifolia, all of which are shoreline species (Table 22). Scarification had a large effect on Zizania aquatica, wild rice, which previously to this showed no germination whatsoever (data not shown). Scarification had a small effect on the

Table 21. The effect of temperature in combination with light and dark periods on seed germination (%).

Plant species	Temperature-light/dark treatment			
	22°C 8h light	22°C total dark	15-8°C 8h light	15-8°C total dark
Alisma plantago-aquatica	0	0	0	0
Alopecurus pratensis	1	75	NT[1]	NT
Beckmania syzigachne	1	1	1	2
Carex aquatilis	2	0	0	1
Deschampsia cespitosa	74	NT	NT	NT
Eleocharis palustris	0	0	0	0
Elymus angustus	88	NT	NT	NT
Glyceria grandis	0	2	1	3
Hordeum jubatum	94	NT	NT	NT
Phalaris arundinacea	37	NT	NT	NT
Rumex occidentalis	97	NT	NT	NT
Sagittaria cuneata	1	0	0	0
Scirpus validus	0	0	0	0
Typha latifolia	0	0	0	0
Zizania aquatica	1	0	0	0

[1] NT - Not Tested.

germination of Carex aquatilis and Sagittaria cuneata. These latter species still only had 4% germination after scarification.

4.6.2.4 Experiment IV: Effect of mulches on seed germination placed in sand-sludge mixtures and pure sludge. The seeds placed on the surface of pure sludge

germinated poorly; those seeds which did germinate were the ones that came to rest just below the surface. Any seeds on the surface of the pure sludge came into contact with residual bitumen, and some, especially reed canary grass (Phalaris arundinacea), were penetrated by it. Seeds which were visibly penetrated or coated by bitumen did not germinate. Alopecurus seeds which were commercially coated with clay were heavy enough to sink just below the liquid surface and did not come into contact with the bitumen.

The use of peat as a mulch on the surface absorbed the bitumen and reduced its penetration into the seed; germination was high where it was used. Seeds grown in the wood fibre mulch germinated poorly; in a number of pots, there was no germination at all. The reason for this was not determined.

Seeds sown on or just beneath the surface of a sand-sludge mixture germinated much better, probably because bitumen did not accumulate on the surface in as great an amount as in pure sludge. Consequently, the use of a peat mulch on sand-sludge mixtures was not as beneficial as it was on pure sludge.

4.6.3 Discussion

The germination of seeds and the establishment of seedlings is the most critical step of the dewatering process. Plant species must have seeds that germinate easily and at fairly low temperatures early in the season in order to have a long growing season.

Rumex occidentalis, or western dock, performs well under nearly all conditions. It has good germination under all combinations of temperature and light and is more tolerant of low temperatures than any other species, even though at 1°-8°C it is dormant longer than at higher temperatures. Rumex occidentalis also shows no ill effect from long seed-storage times. After 1 year, the germination was still 100%.

Phalaris arundinacea and Alopecurus arundinacea, while slower establishing than Rumex occidentalis, do germinate under conditions of low temperature. Alopecurus

Table 22. The effect of immersion in water and scarification on the germination of aquatic plant species.

Plant species	Observations
Alisma plantago-aquatica	Scarified; 70% in 1 day
Carex aquatilis	Scarified; 4% in 7 days, no further germination
Carex rostrata	None germinated in 45 days
Eleocharis palustris	2% in 13 days, no further germination
Juncus balticus	80% in 4 days
Sagittaria cuneata	Scarified; 4% in 6 days, no further germination
Scirpus validus	No germination
Typha latifolia	60% in 15 days
Zizania aquatica	No germination without scarification; 90% after 2 days in light with scarification

pratense has the ability to germinate in the dark, a condition that could be encountered often if it were planted on the surfaces of pure sludge.

Typha germinated well in wet conditions, but showed no germination when tested for a response to varying light-dark regimes. Typha also performed poorly on sludge and sand-sludge mixtures; plants grew to 30 cm and then the leaves began to yellow and die. It was dropped as a suitable species for dewatering the oil sand materials.

Peat mulch appears to be useful in starting seeds and promoting establishment. It absorbs bitumen, prevents seed damage, keeps the seed moist, and can act as a carrier for the seeds during the seeding process. Mulches may have another useful function: those seeds which require light for germination may not receive the necessary exposure if they are buried too deeply in the sand-sludge mixtures or in pure sludge, which is opaque. A mulch would keep the seeds on the surface and transmit

enough light to promote germination. The optimal thickness of mulch can be calculated on the basis of cost and the minimum amount required to protect the seed.

5.0 THE DEWATERING OF PURE OIL SANDS SLUDGE

Dewatering research on pure (unamended) oil sands sludge up to 1986 concentrated on finding methods to improve its settling properties, ignoring the fact that the biggest problem was consolidation and not a failure to settle (J.D. Scott, University of Alberta, personal communication). The work on consolidation assumed that sand amendments were needed in some way because of the slow-consolidating characteristics of the sludge observed on the bottom of the tailings pond. Furthermore, the total water loss needed from pure sludge, starting at 30% solids, was two-thirds more than that needed from 3:1 sand-sludge mixtures, starting at 50% solids. Since water loss was slow even from the sand-sludge mixtures, it was probable that the time required to dewater pure sludges would prohibit commercial dewatering on a large scale.

Then, in 1986, Leon Koverny, a technician at the Alberta Environmental Centre, experimented with the effect of freezing and thawing on oil sands sludge. He confirmed earlier work[2] that water could be forced out of the oil sands sludge by freezing and that the water would collect on the surface of the sludge after thawing. This led to a series of laboratory tests and large field-scale demonstrations.

The cost of sludge dewatering could be reduced because it is expensive to mix sand with sludge. Material-handling systems could be designed to closer specifications because the unpredictable segregation of sand-sludge mixtures could be avoided entirely.

But new problems loomed. Although much was known about the engineering properties of sand-sludge mixtures, little was known about the biological or physical properties of pure sludge. Sections 5.1 through 5.4 examine the effects of freezing and thawing on the solids content of oil sands sludge. Sections 5.5, 5.6 and 5.7 discuss the limitations to draining the expressed water from the surface of oil sands sludge. Although freezing and thawing will convert fresh sludge (30% solids) to partially

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[2]Personal communication, June, 1990, Dr. George Lesko, Syncrude Canada Ltd., that Canada patent #973,300 (1973) and U.S. patents #3,351,358 (1973) and #4,088,682 (1977) cover the use of freezing and thawing to dewater pure (unamended) oil sands sludge.

dewatered sludge (50% to 60% solids), another 20% water must be lost to achieve a stable surface. Reed canary grass was chosen to complete the dewatering cycle; its fertilizer requirements are outlined in Section 5.8.

5.1 SMALL-SCALE LABORATORY TESTS: DEWATERING BY FREEZE-THAW

Several studies report dewatering of sewage sludges to higher solids content by a simple freeze-thaw operation (Farrel et al. 1970; Reed et al. 1986; Rush and Stickney 1979). Impetus for this work has been the high cost and complexity of the mechanical dewatering processes. Results from these studies were quite variable owing to the wide range of industrial and municipal sludge types examined. In extreme cases, freeze-thaw dewatering of dilute sludges (treated with flocculents) yielded up to a ten-fold increase in percent solids. It was important to see if the clay sludges from oil sand tailings would dewater in a similar manner.

A physical dewatering scheme would complement the work being carried out at the Alberta Environmental Centre in biological dewatering. Sludge of higher solids content would be more favourable to establishing plants or grasses for further biological dewatering and natural consolidation to solids in excess of 80%.

5.1.1 Materials and Methods

The Syncrude tailings pond sludge used throughout this experiment came from a 20,000 L batch obtained in September, 1986. The initial lot had 29% solids; the final lot had 35% solids owing to self-consolidation in the temporary storage tank prior to drumming.

The sludge was well mixed to ensure homogeneity, and all freeze-thaw experiments were carried out with "pure" sludge. Samples were taken in each experiment for oven drying (130°C) to establish the percent solids prior to freezing.

The sludge was frozen at the Alberta Environmental Centre in a freezer at -24°C and outside at ambient winter temperatures. Sludge batch sizes varied from 3 kg

to 20 kg to determine if sludge depth was a factor in the degree of dewatering. The sludge was left in the freezer for 24 h; outside freezing took several weeks. Thawing was done at room temperature (22°C). Containers used for the tests were insulated on the bottom with a slab of 2.5-cm polystyrene foam.

Once the sludge thawed, the supernatant water was decanted and weighed. The concentrated sludge was sampled and oven dried at 130°C to confirm the percent solids. In the initial set of experiments, the freeze-thaw procedure was continued to determine the percent solids achievable for three consecutive cycles. A summary of the methodology follows:

Sludge batch size .... 3 to 20 kg
Sludge depth .... 5 to 30 cm
Freeze-thaw .... 1 to 3 cycles
Water .... decanted and weighed
% Solids .... oven dried @130°C

The analytical methods used to characterize the thaw water are described in a publication of the Alberta Environmental Centre (1987). The toxicity of the water was tested using a Microtox bioassay.

5.1.2 Results and Discussion

Frozen sludge surfaces displayed networks of needle-like ice crystals up to 6 cm in length. A core showed that the crystal network extended through the entire depth of the sludge.

During thawing, water pooled on the surface of the sludge. As thawing progressed, the sludge appeared to subside or settle in grains or platelets, forcing more water to the surface. A one-day freeze-thaw procedure produced grainy sludge sediment. Slower freezing (2 weeks) produced platelet size sediment, up to 0.7-cm long. Despite the rate of freezing, the extent of dewatering was nearly the same (52% to 54% final solids from 35% starting material).

Both the 29% and 35% solids sludge dewatered to nearly 50% solids in one freeze-thaw cycle (Table 23). Additional freeze-thaw cycles enhanced the solids content in lesser increments.

Water released from thawing sludge looked clear. The water surface contained visible streaks of oil, but some oil, or bitumen, remained in the solid sludge (4.5% toluene extractable, dry weight basis). The chemical properties of the thaw water are summarized in Table 24.

Despite the clarity of the thaw water, the chemical analysis showed a high level of dissolved ions and solids--significantly higher than that reported for tailings pond water from Syncrude Canada Ltd.'s main holding area (MacKinnon and Boerger 1986). The concentration of the thaw water required to produce a 50% (EC_{50}) decrease of light from the Microtox assay was greater than 100%, signifying that it was non-toxic as evaluated by this test.

5.2 SMALL EXPERIMENTAL MODELS OF FREEZE-THAW SYSTEMS

It was demonstrated that one freeze-thaw cycle liberated up to half the water in a 29% to 35% solids content oil sands sludge. Additional freeze-thaw cycles increased the solids content to approximately 57%. The water liberated in the process was decanted or "surface drained". In this phase of the work, alternate strategies are examined for enhancing drainage during the freeze-thaw dewatering process.

Water is concentrated during the freezing cycle into ice crystals or "lenses" within the mass of the sludge. Sludge is partitioned and compacted within the ice crystal lattice. During thawing, this lattice is transformed from ice to water with a momentary opening of flow channels enabling the water to move upward. Flow of water continues until the clay particles consolidate sufficiently to stop further dewatering. Taking advantage of the opening of water channels to drain water more quickly would enhance dewatering. Furthermore, water collecting on the surface after the thaw portion of the cycle needs to be drained before the surface can begin drying by evapotranspiration.

Table 23. The effect of freeze-thaw cycles on solids content (%) of pure sludge.

29% sludge starting material	Percent solids by freeze-thaw cycle		
Sludge depth	1	2	3
5 cm	45	48	-[1]
15 cm	47	52	54
30 cm	43	50	53
35% sludge starting material			
15 cm	51	55	57

[1] - = no measurement made.

Tailings sand is available in abundance at all oil sand processing sites and, therefore, was used in the following dewatering models.

5.2.1 Materials and Methods

Pure oil sands sludge, at 35% solids content, and dyke sand were used in these dewatering models. The sludge was used without any additives. The moisture content of the sand was adjusted by the addition of water.

The sludge used in the small models was frozen in a walk-in freezer at -24°C; the sludge for the larger models was frozen outside at the Alberta Environmental Centre under ambient winter conditions. Model sizes were scaled from lab sizes of several litres (12 kg) to outdoor sizes of 200 L (0.2 m^3). Indoor thawing was done with the assistance of a heat lamp, and outdoor thawing was done under ambient conditions. The small lab models were insulated or uninsulated to suit the required boundary conditions.

Water drained through sand and then into tubes penetrating the container walls and in contact with the sand at desired locations.

Table 24. Chemical properties of sludge thaw water[1].

Property	Units	Thaw water values
pH	pH units	8.4
Conductivity	dS/m	4,090.0
Dissolved solids	mg/L	3,040.0[2]
Turbidity	NTU	0.6
C.O.D.	mg/L	14.0
Oil & grease	mg/L	3.0
Phenols	mg/L	0.03
Cyanide	mg/L	0.002
Major Ions		
Sodium	mg/L	770.0
Potassium	mg/L	19.0
Magnesium	mg/L	25.0
Calcium	mg/L	35.0
Chloride	mg/L	1,125.0
Sulphate	mg/L	12.0
Bicarbonate	mg/L	407.0
Fluoride	mg/L	1.2
Nutrients		
Dissolved Organic	mgC/L	16.5
Total Kjeldahl	mgN/L	7.3
Nitrite + Nitrate	mgN/L	0.02
Ammonia	mgN/L	7.3
Phosphate	mgP/L	0.01

[1] All thaw water was collected to form a composite sample; only one analysis was carried out.

[2] By evaporation.

Several basic dewatering models were used (Figure 17). The simplest models were rectangular polystyrene crates configured to have the sludge drain into a single channel in the middle or to any surrounding side. The concentric models were built so that the sludge was surrounded by sand on the bottom and sides, and drainage could only be through the sand. There was no possibility of water "short circuiting" along the container walls. The surcharge model with the sand layer on top of the frozen sludge was designed to test a drainage scheme that might be scaled to fit field conditions where the sand surcharge might force more water out by its added load.

All tests on dewatering models were conducted one time only.

5.2.2 Results and Discussion

Table 25 summarizes the effect of drainage configuration on the dewatering of 35% solids sludge during a single freeze-thaw cycle. The simplest model, rectangular with a sand channel in the middle, duplicated the typical dewatering condition used in the previous freeze-thaw studies. There was only a 17% increase in solids content using this configuration. By altering the potential drainage area and surrounding the sludge with sand, substantially more water was removed (second rectangular and concentric models, Figure 17, Table 25). The high sand-sludge contact area permitted the sand capillary forces to draw more water out than was possible by gravity drainage alone. The highest dewatering in the concentric model was achieved using moist (11% dry weight basis) sand. The final percent solids in this case was 63%. Using saturated sand (24% moisture), the attainable percent solids was 59% to 60%.

The surcharge model had a moderately high sand-sludge contact surface and an applied overburden pressure on the sludge. Dewatering to 57% solids content was achieved in this test. This model was of practical interest owing to the ease of field trial implementation.

The largest-scale drainage tests were done outside. A children's plastic wading pool (0.9-m deep) was half-filled (half a circle) with damp sand and the other half

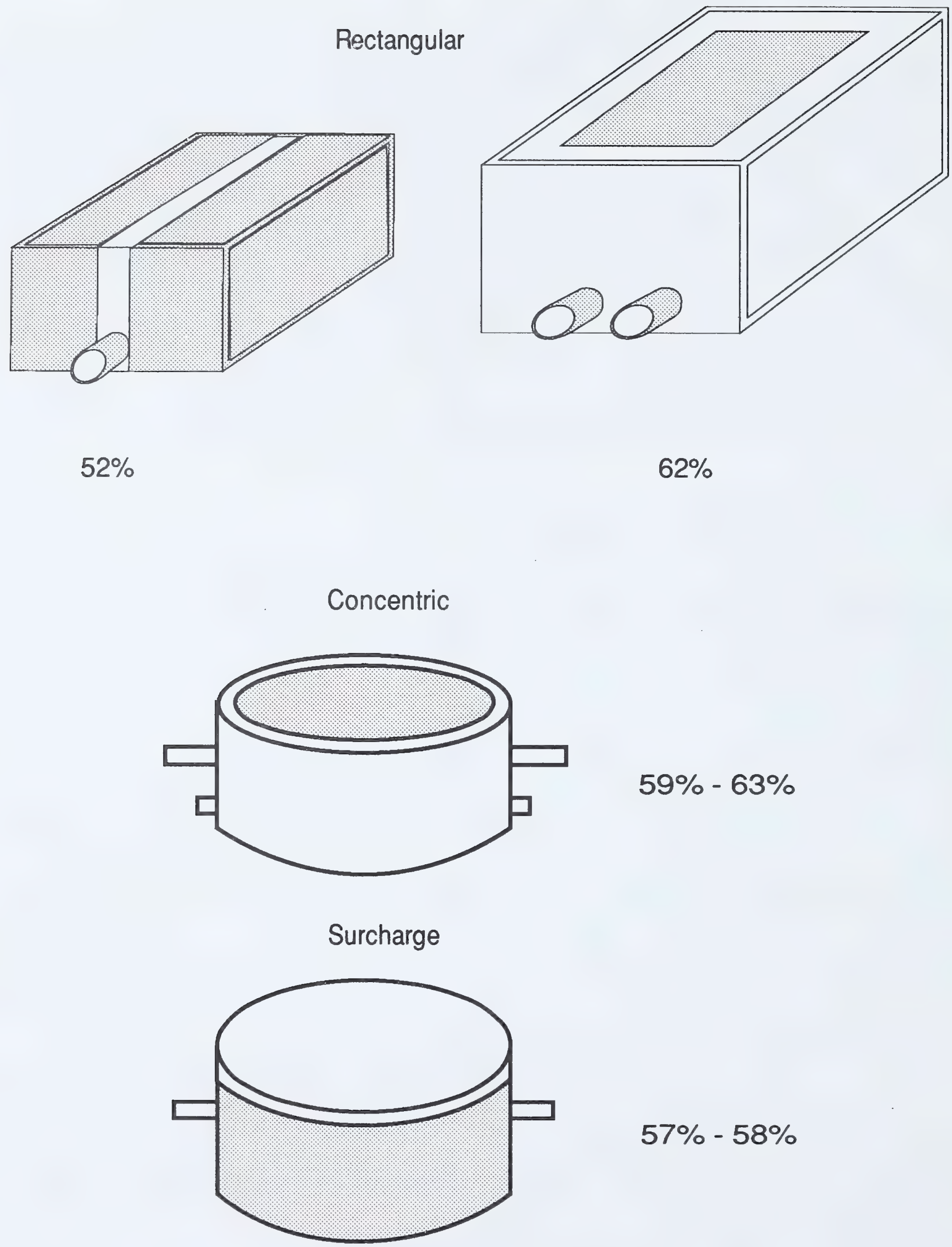


Figure 17. Experimental models for dewatering pure oil sands sludge (unreplicated), with final solids content (%).

was filled with 35% solids sludge. During the first spring thaw (April 1987), expressed water was rapidly absorbed by the sand. Fifty six percent solids was achieved at complete thaw, and the sludge was dewatered further by evaporation. At 75% solids, the sludge was planted to reed canary grass.

Table 25. The effect of sand-sludge configuration on the increase of sludge solids content after freezing and thawing.

Configuration[1]	Sludge solids content (%)		
	Initial	Final	Increase
Rectangular (sand in middle)	35	52	17
Rectangular (sand around sides)	35	62	27
Concentric	35	59 to 63	24 to 28[2]
Surcharge	35	57	22

[1] Configurations are shown diagrammatically in Figure 17.
[2] Variance arises from two samples taken from the same model.

5.3 A LARGE-SCALE LABORATORY TEST: DEWATERING SLUDGE BY STATIC FREEZE-THAW

Freeze-thaw dewatering originated in more temperate climes in the northern part of the United States where biological sludges of low solids content were treated. The water content of Syncrude sludge is lower, the ambient winter temperatures in Fort McMurray are colder, and the season is longer. Therefore, it was logical to assume that freeze-thaw would be a viable solution. Early freeze-thaw testing on Syncrude sludge displayed dramatic increases in percent solids (Section 5.1).

A wide range of sludge concentrations was subjected to three consecutive freeze-thaw cycles to test the applicability of the Neuman-Stefan formula, which predicts

the depth to which the sludge can be frozen by establishing the relationship between initial solids content and the Neuman-Stefan proportionality coefficient (m).

5.3.1 Materials and Methods

The experimental units were constructed by placing an interior metal drum into an exterior polyethylene drum along a concentric axis (Figure 18). To simulate natural freezing conditions, insulation was inserted between the two containers, thereby forcing the freezing isotherm to progress from the surface down.

The units were filled with sludge at four initial solids contents: 15%, 25%, 35%, and 45% solids, wet weight basis. These were prepared by sequentially diluting a batch of sludge at 53% solids with reverse osmosis-deionized water. After completing each dilution, three experimental units were filled to a depth of 46 cm, providing an initial volume of 45 L.

Sludge sampling inside the barrels was conducted before the initial freezing and after every freeze-thaw cycle. All replicates were randomly sampled at three depths: one-sixth; one-half; and five-sixths of the total sludge depth. The sample sites were selected from a random number table where each number corresponded to a grid intersection placed over the sludge surface for this purpose. The percent solids of the samples was determined by mass measurements before and after oven-drying (105°C for 24 h).

One replicate of each treatment was instrumented with type T thermocouples connected to a Campbell Scientific CR10 micrologger. Thermocouple leads were run from the instrumented units to the microloggers located outside the freezer. The temperatures were recorded every half hour. The freezer temperature was kept at -24°C throughout the experiment. When all thermocouples within the frozen sludge reached at least -24°C, the freezing period was considered complete. The twelve units were arranged randomly (completely randomized design) inside the freezer.

To design field operations for future freeze-thaw demonstrations, proportionality coefficients used in the Neuman-Stefan formula were derived for the various sludge concentrations. This formula is given as:

$$x = m\sqrt{\Delta T \cdot t} \qquad (\textit{Equation } 12)$$

where

x	=	depth of freezing, cm.
m	=	proportionality coefficient depending on the thermal conductivity, density, and latent heat of material being frozen, cm ($\sqrt{°C.days}$)
$\Delta T \cdot t$	=	freezing index, °C.days
ΔT	=	difference between the freezing temperature and average daily ambient temperature, °C
t	=	time period of concern, days.

Rearranging the formula allows for the determination of m:

$$m = \frac{x}{\sqrt{\Delta T \cdot t}} \qquad (\textit{Equation } 13)$$

Freezing times were recorded at four depths within each mixture. Due to equipment error during the early part of the first freezing cycle, some measurements were lost.

All units were removed from the freezer at the same time. During thaw, surface bitumen was skimmed before periodic removal of water. Two days into the thaw period, the units were covered with lids to prevent moisture loss owing to evaporation. Thawing was considered complete when all thermocouples reached a minimum temperature of +20°C. The last thaw water was removed, and the units were then sampled for solids content, as noted previously. This constituted the end of the first freeze-thaw cycle.

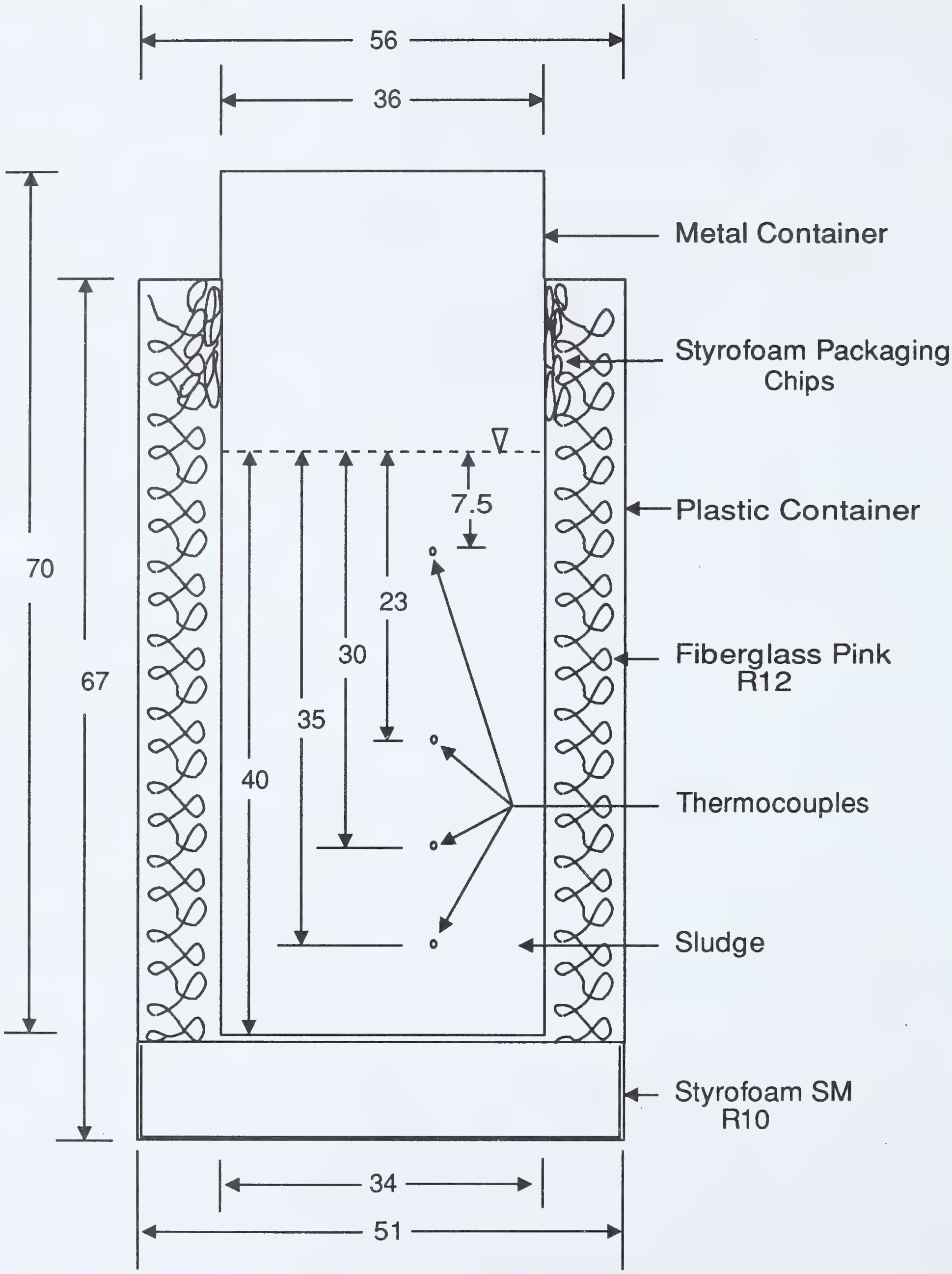


Figure 18. Instrumented insulated barrels used in laboratory freezing and thawing (all dimensions in cm).

The freeze-thaw process was repeated twice more to complete the experiment.

5.3.2 Results

During the first freeze-thaw cycle, the metal drum of replicate 2, mix 1 (45.4%) ruptured and was removed from the experiment. The failure was caused by excess strain induced on the container by expansion stresses incurred during a previous experiment. The remaining eleven drums were new and did not fail during the first freeze-thaw cycle. Upon disassembly of the drums, it was discovered that replicate 1 of mix 2 (37.4%) failed during the second freezing cycle. Data collected from this unit beyond stage 2 were deemed invalid and were not used in calculations presented in these results.

The sludge concentrations before and after each freeze-thaw cycle are given in Table 26. Individual values represent the average of samples taken at three depths within the respective replicates of each mix. There are small differences between the intended and actual solids contents, but the largest variance was only 2.4% (mix 2 was intended to be 35% and, in fact, reached 37.4%). Overall, the desired range of solids content was achieved. It is apparent that while each freeze-thaw cycle dewatered the sludge to some extent, early cycles were more effective than later ones.

The cumulative change in percent solids after each cycle is presented in Figure 19. In this case, the percentage on the ordinate represents the change from the original solids concentration. The graph provides a relative comparison of single versus multiple freeze-thaw applications. Multiple freeze-thaw cycles had a greater effect on water release from sludges with low solids content than from sludges with high solids content. The effect of initial solids content on the amount of dewatering is dramatic. Mix 1, starting at 45% solids, had a cumulative increase of only 35% over three freeze-thaw cycles. On the other hand, mix 4 started at 16% solids and finished after three cycles at 49.5% solids, a 200% cumulative increase! The two intermediate dilutions also

Table 26. Average percent solids (n = 9[1]) before and after freeze-thaw cycles.

Mix #	Original % solids	% Solids after 1 cycle	% Solids after 2 cycles	% Solids after 3 cycles
1	45.4	51.3	57.8	60.4
2	37.4	47.9	55.1	59.6
3	26.2	38.7	46.4	52.7
4	16.3	35.4	46.2	49.5

[1] Average of 3 depths x 3 replicates, except mixtures 1 and 2 which were missing 1 replicate each (n = 6).

had intermediate cumulative increases in solids content (Figure 19), indicating a correspondence between initial and final solids content.

The relationship between initial solids content of oil sands sludge and the degree of dewatering through freeze-thaw was exponential (Figure 20). Low initial solids content resulted in a large amount of dewatering. As the solids content increased, the rate of dewatering dropped quickly. The exponential decrease in rate of dewatering was independent of the freeze-thaw cycle, which acted only as a determinant of "initial" solids content. The prediction of final solids content of oil sands sludge undergoing freeze-thaw can be made confidently without considering the previous freeze-thaw history of the sample:

$$Y = 249.4 - 8.93x + 0.08x^2 \qquad \textit{(Equation 14)}$$

where

Y = final solids content [%]

x = initial solids content [%]

The coefficient of determination (r^2) is high (0.94). Only 6% of the variation in final solids content is not accounted for by the initial solids content.

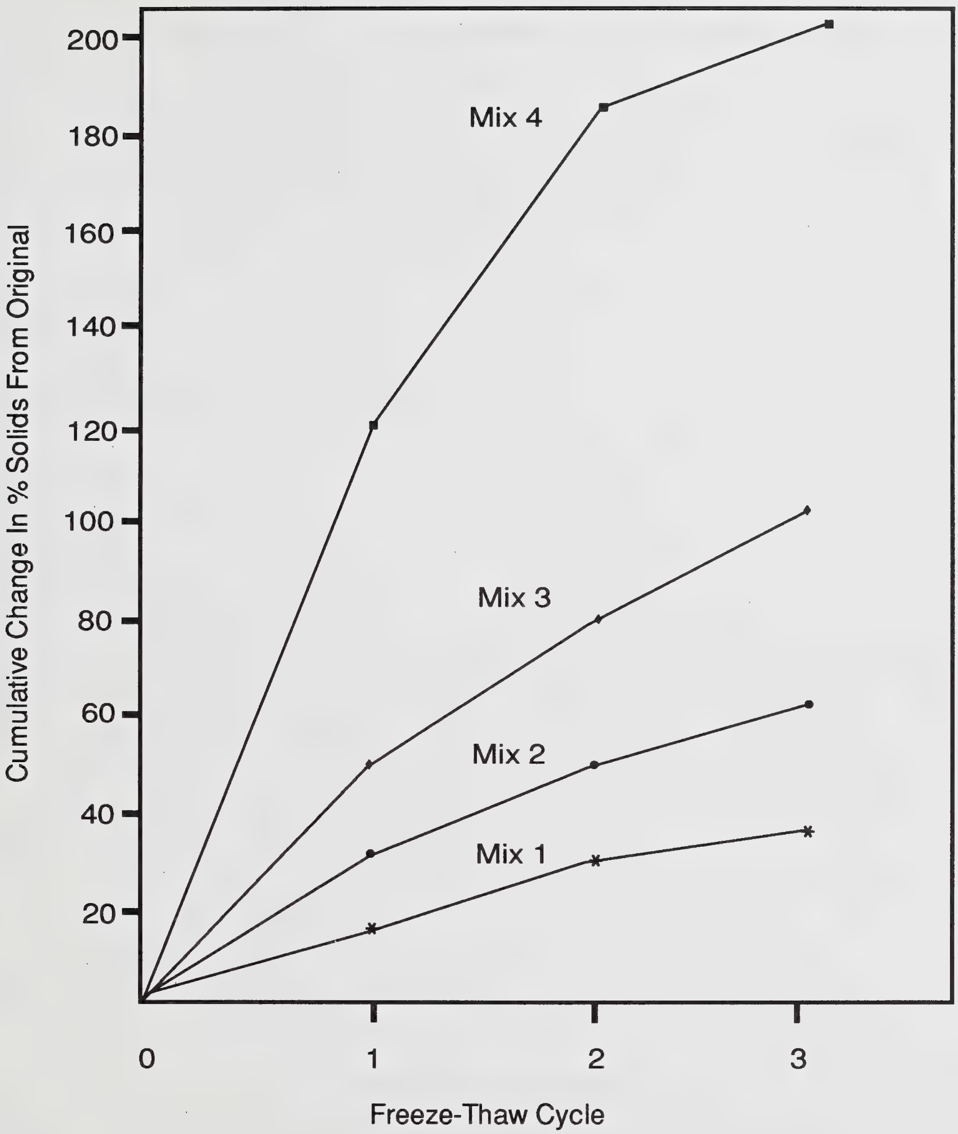


Figure 19. The cumulative increase in percent solids through three freeze-thaw cycles.

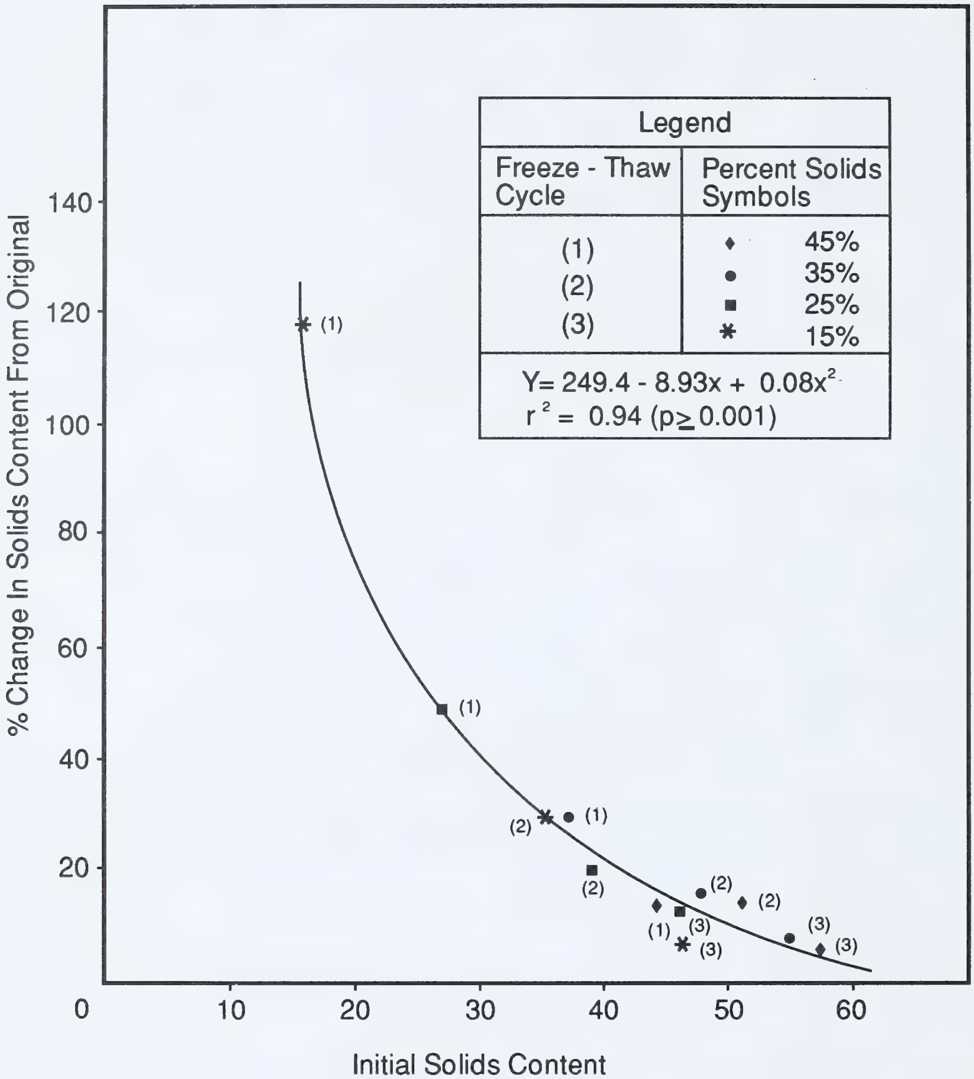


Figure 20. The change in final solids content in relation to initial solids content and freeze-thaw cycle.

Longer freezing periods were necessary for mixes of lower solids content with equal volumes (Table 27). The higher the solids content the less energy that was needed to change a given volume of mix from liquid to ice.

The proportionality coefficients for sludges of various solids content were computed from information collected at the deepest thermocouple (38.1 cm) during the first freeze-thaw cycle. The relationship between the original solids content of the sludge and the calculated proportionality coefficients are given in Table 28. For solids contents less than 45%, a linear relationship exists:

$$m = 0.0128\ (\textit{original \% solids}) + 2.387, \qquad (\textit{Equation}\ 15)$$

with a correlation coefficient, r, of 0.998. For solids contents greater than 45%, this relationship is not valid.

5.3.3 Discussion

The experimental results confirm previous findings that the freeze-thaw process increases the solids content of Syncrude sludge (Section 5.1). The mineral fines originating from bitumen extraction processes have less than 2% organic content (Scott et al. 1985), but acted like sewage sludges when subjected to freeze-thaw conditions (Rush and Stickney 1979). The sludge suspensions with the lowest solids content, mineral or organic, dewatered to the greatest extent. There was an exponential decrease in the amount of water released as pre-freezing solids content increased. Multiple freeze-thaw cycles caused a progressive loss of water, but the same exponential relationship applied between the original solids content and the amount of water lost. That is, the second and third freeze-thaw cycles acted on mixes with a higher solids content and, therefore, there was an exponential decrease in the amount of water lost with each cycle.

The oil sands sludge tested in this experiment reached a maximum of 60% solids content, if subjected to enough freeze-thaw cycles (Table 26). On an operational

Table 27. Freezing times per unit volume for each mix during cycle 1 (one replication only).

Cycle #	Mix #	Pre-cycle % solids	Time to freeze (h)	Pre-cycle volume (L)	Freezing time/ volume index (h/L)
1	1	45.4	125	45.0	2.78
1	2	37.4	177	45.0	3.93
1	3	26.2	195	45.0	4.33
1	4	16.2	217	45.0	4.82

Table 28. Neuman-Stefan proportionality coefficients (m) for various sludge concentrations (based on one replication only).

Original	Freezing time		m
% solids	h	days	
45.4	125	5.208	3.41
37.4	177	7.375	2.86
26.2	195	8.125	2.73
16.3	217	9.042	2.59

basis, the sludge accumulating at the bottom of the tailings pond on the Syncrude Canada Ltd. lease consolidates to 30% solids in 2 to 5 years. According to the equation 14, page 100, if sludge were exposed to ambient temperatures, one winter of freezing and thawing would yield sludge at 45% to 55% solids content. This was corroborated in two recent field experiments conducted at Fort McMurray (Sections 6.2 and 6.3).

One reclamation scheme for oil sands sludge involves the use of plants to dewater sludge through evapotranspiration. To establish plants successfully, a relatively firm seed bed is needed, corresponding to approximately 50% solids content. One winter

of freezing and thawing will produce the desired seed bed conditions, a sludge surface at 45% to 55% solids, depending on the depth of sludge frozen, the type of drainage employed, and the amount of moisture lost through evaporation before plants are established.

The proportionality coefficients for the Neuman-Stefan formula had a linear relationship to the original solids contents. This formula is used to estimate the depth of freezing achievable in a selected time period (Reed et al. 1986) and can now be used confidently to design facilities and treatment programs for oil sands sludge where the thickness of individual layers and the time periods for freezing are critical constraints. Work that investigated a dynamic (multiple layer) freeze-thaw process for oil sands sludge is reported in Section 5.4.

5.4 A LARGE-SCALE LABORATORY TEST: DEWATERING SLUDGE BY LAYERED FREEZE-THAW

The objective of this experiment was to determine the effect of freezing in incremental layers and subsequent thawing on the percent increase in solids and decrease in volume of oil sands sludge. The results of this experiment were compared to the results from an earlier freeze-thaw experiment which used "static" freezing and thawing (Section 5.3).

5.4.1 Materials and Methods

The oil sands sludge at 25% solids content (wet weight basis) by diluting existing sludge (32%) with reverse osmosis-deionized water.

The experiment consisted of three replicates. Each replicate was placed in the same experimental units described in the previous section (5.3) and shown in Figure 21.

Replicate one was instrumented with eight copper-constantan (type T) thermocouples. Figure 21 shows the thermocouple locations and numbering arrangement. The thermocouples were situated so that one thermocouple was located 1 cm from the

bottom and another thermocouple was located at the midpoint (5.7 cm) of each 11.4-cm sludge layer.

The thermocouples were calibrated by constructing an ice bath as shown in Figure 22 and measuring the triple point of water. The thermocouple ends were surrounded by a film of silicon to prevent corrosion. The thermocouple ends were placed in the ice bath and the temperatures were measured using a Fluke 2168A digital thermometer. All thermocouples measured temperatures of 0°C. For a further check, the thermocouples measured the freezer and pilot plant temperatures; all thermocouples were within 1.2°C for the freezer and within 1°C for the pilot plant.

The percent solids of sludge was determined by drying 20 to 60-g samples in an oven at 105°C for 24 h. All percent solids were based on wet weights.

Sludge was mixed with a drill and impeller. The impeller had three square paddles extending from the shaft.

Four layers of sludge were poured. The thickness of the sludge layers was based on the amount of sludge that would freeze in 24 h. Using the Neuman-Stefan formula (Equation 12, page 97):

$$x = m(\sqrt{\Delta T \cdot t})$$

A value of 2.71 was used for the proportionality coefficient, m, from the previous bulk freeze-thaw experiment (Section 5.3). Twenty four hours was chosen as a reasonable time span for freezing. A maximum depth of 15.9 cm/day was calculated using the Neuman-Stefan formula. Four, 11.4-cm layers were chosen to guarantee the full freezing of each layer in 24 h, as well as to maximize the number of layers.

Before each layer was poured, the sludge was mixed with the drill and impeller. Samples were taken at the midpoint of each layer and analyzed for solids content. After the first layer was poured, the three replicates were placed in the freezer at -24°C. Temperature monitoring began at this point. When both thermocouples in the

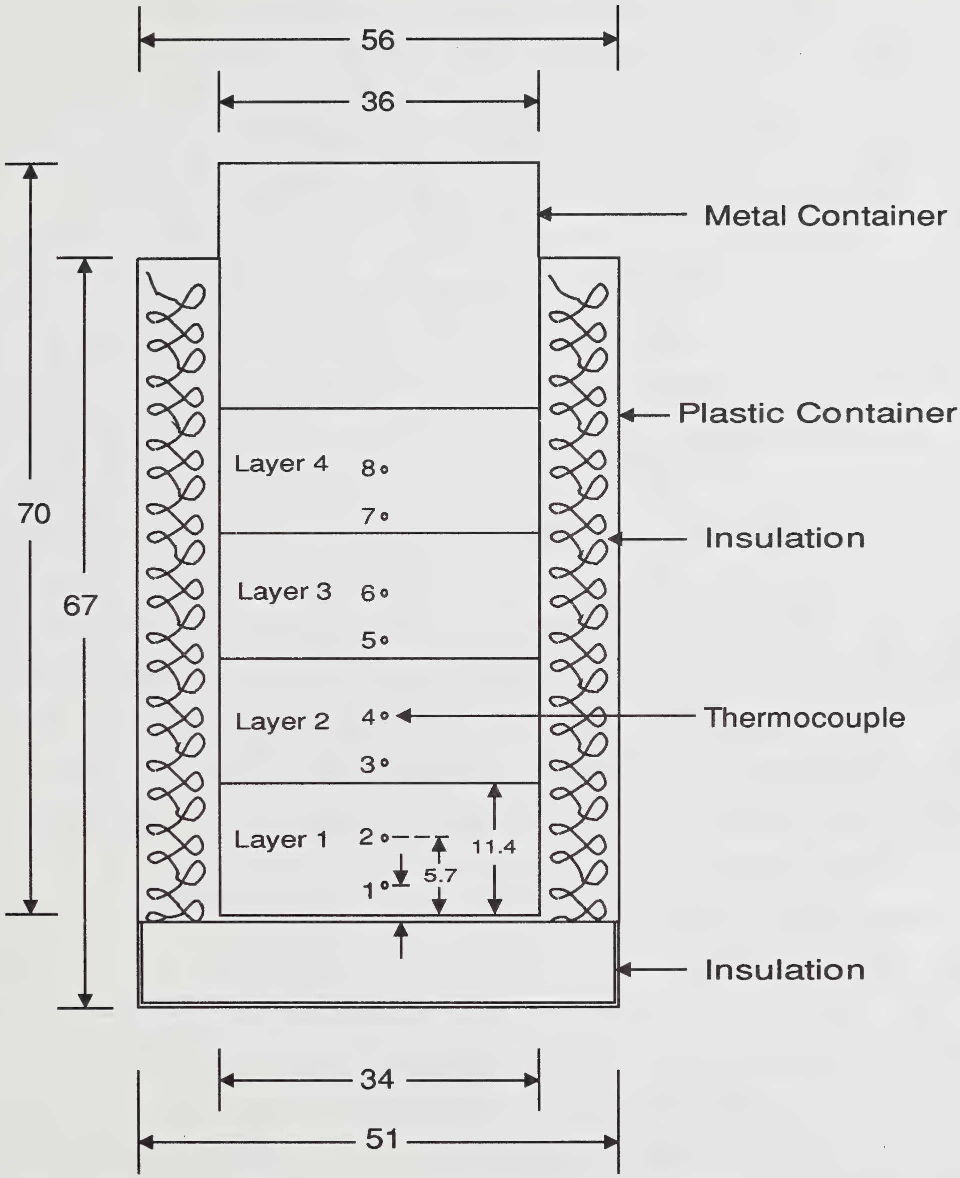


Figure 21. Replicate composition and thermocouple arrangement. (Note: all dimensions are in centimetres).

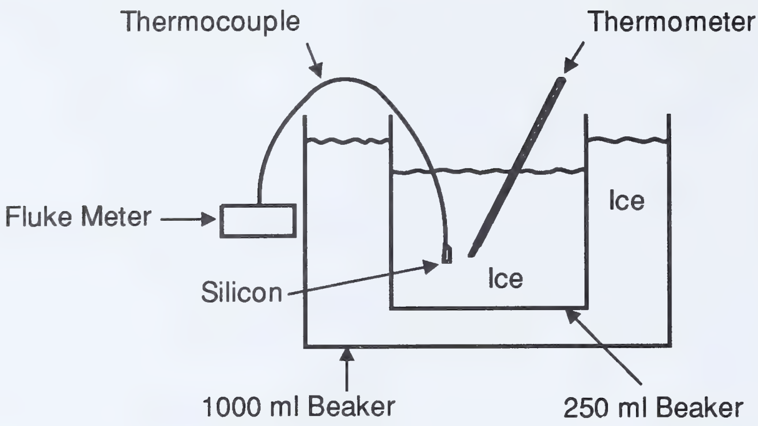


Figure 22. Diagrams of experimental apparatus used to measure triple point of water.

first layer (1 and 2) reached temperatures less than -5°C, a second, 11.4-cm layer of sludge was added to the three replicates in the freezer. This procedure was repeated until four layers of sludge were frozen. Temperatures were recorded every hour using a Campbell Scientific CR10 micro-logger. The micro-logger was able to record only six thermocouples simultaneously. Since the experiment contained eight thermocouples, the two thermocouples in the top layer (thermocouples 7 and 8) were left disconnected until the fourth layer was ready to be poured. At that time the two thermocouples in the bottom layer (thermocouples 1 and 2) were disconnected and replaced by thermocouples 7 and 8. Upon thawing, thermocouples 1 and 2 were left disconnected until the top layer reached a temperature in excess of 10°C. Then thermocouples 7 and 8 were disconnected and replaced by thermocouples 1 and 2.

The three replicates remained in the freezer until all four layers reached -24°C (for consistency with the previous experiment). The sludge was then removed from the freezer and allowed to thaw. Lids were placed on the containers to ensure no loss of water by evaporation. Once the replicates reached room temperature, temperature recording stopped and the thaw water was siphoned off and kept separate for each

replicate. The volumes of water were recorded. Samples were then taken at one-sixth, one-half, and five-sixths the total sludge depth and measured for percent solids. The samples were taken at random locations which were determined using a random number table. All samples were taken at least 5.1 cm away from the edge of the container.

5.4.2 Results

The average solids content of the sludge after freezing and thawing was 44.5%, with the bottommost layer having slightly higher solids content than the others (Table 29). The reduction in sludge volume caused by freezing and thawing was 49%. The time taken to freeze 45.6 cm of sludge to -24°C using layered freezing was 267 h. Table 29 shows the freezing (<-5°C) and thawing (to >0°C) times for each layer. The first layer took longer to freeze than subsequent layers because all components (barrels, insulation, etc.) were at room temperature before the experiment began.

All four layers followed a similar temperature trend (as shown in Figure 23 for layer 2). Initially, the temperature quickly dropped to 0°C. Then, for approximately 30 h, the temperature hovered between 0°C and -5°C while the latent heat was released. For example, at 1 cm from the bottom of layer 2 (thermocouple 3), the temperature dropped from 8°C to 0°C in 5 h; however it took 25 h to drop from 0°C to -5°C.

Layers 2, 3, and 4 cooled from the top and the bottom. Figures 24 and 25 show the freezing curves for layers 1 and 2. The freezing curves for layers 3 and 4 were very similar to layer 2.

Figures 24 and 25 also show that when a warm layer of sludge was poured on top of a frozen layer, the temperature of the frozen layer directly below rapidly increased to approximately -2°C and remained constant until the new layer was frozen. Then, the temperature cooled at the same rate as the new layer above.

When warm (room temperature) sludge was poured over several layers of previously frozen sludge, the frozen layer directly beneath the new layer acted as an

insulator (Figure 24 when layers 2 and 3 were poured; Figure 25 when layers 3 and 4 were poured). This resulted in:

1. less than a 5-h delay in the bottom layer reacting to heat added in the newly poured sludge; and
2. a temperature rise in the buried frozen layer to approximately -4°C, where it remained constant for over 20 h.

The rise in temperature of the frozen sludge at depth when a new layer was poured indicated that heat transfer occurred from the bottom of the sludge pool (in this case, the barrel) as well as from the top.

Examining Figure 24 in detail shows the following: when layer 2 was poured, the temperature of layer 1 increased from -11 to -1.4°C. When the third layer was poured, the temperature of layer 1 increased from -22.3 to -3.7°C. This explains why it took so long to freeze all four layers to -24°C. When a new layer was poured, the system (a barrel full of frozen sludge at -24°C) acted as if it were just one layer with a starting temperature of approximately -3°C. The bottom layers did not show extreme drops in temperature until the sludge above was frozen. Then, everything cooled rapidly.

It took 227 h for the layered sludge to thaw. During the thaw period, the sludge layers exhibited similar trends (Figures 26 and 27). The first stage was a rapid increase in temperature to -1°C. The next stage depended on layer position. The lower the layer, the more time required to absorb the latent heat necessary to change solid into liquid. The final stage was an increase in temperature to ambient conditions. Layers 2 and 3 (data not shown) showed temperature profiles with identical trends, but the time periods corresponded to intermediate values of those shown for layer 4 and layer 1, as shown in Figures 26 and 27, respectively.

The bottom of the bottommost layer (thermocouple 1, Figure 27) thawed earlier than the midpoint of the same layer (thermocouple 2). This indicated that some heat transfer was occurring from the floor into the barrel.

Table 29. Time required to freeze (<-5°C) and thaw (>O°C) successive, 11.4 cm layers of oil sands sludge and the resulting solids content by layer (one replication only).

Layer	Position in drum	Time required[1]		Final solids[2] (%)
		Freeze (h)	Thaw (h)	
1	Bottom	49	227	43.5
2	Next-to-bottom	30	224	
3	Next-to-top	27	168	43.5
4	Top	19	91	46.4

[1] Freezing time for each layer poured separately; thawing time cumulative for each layer within the mass of sludge.
[2] Final solids contents were measured at 1/6, 1/2, and 5/6 of the depth of the thawed sludge.

The similarity in temperature profiles of each layer during thaw is demonstrated in Figure 28. There was a rapid increase in temperature in all layers as soon as the thaw regime began (from -24°C to -4°C in less that 20 h). All layers held at -2°C, approximately, until the layer immediately above thawed completely. On average, after the sludge reached -1°C, it took 5 to 6 h per centimetre depth to thaw the sludge.

5.4.3 Discussion

The layered freezing technique was more effective than static freezing in increasing solids content and reducing sludge volume (Table 30). In fact, the layered freezing improved dewatering by 40% over the static technique. In turn, this increased the volume reduction by 5% overall, or 10% more than the static technique.

Before this experiment was begun, it was assumed that static freezing would be slower than layered freezing. Static freezing would always have frozen sludge acting as an insulation over unfrozen sludge. It was assumed that layered freezing would

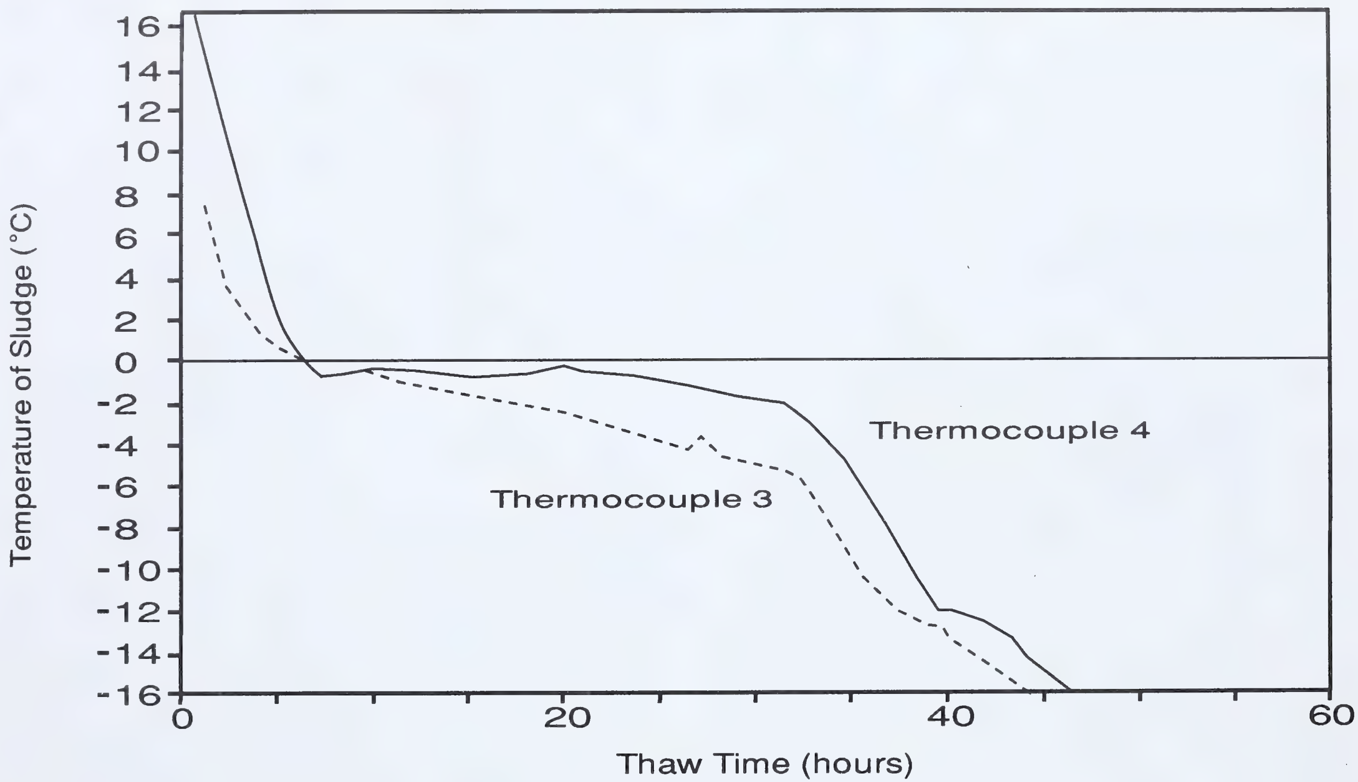


Figure 23. The temperature of layer 2 (as registered by thermocouples 3 and 4) over 45 h.

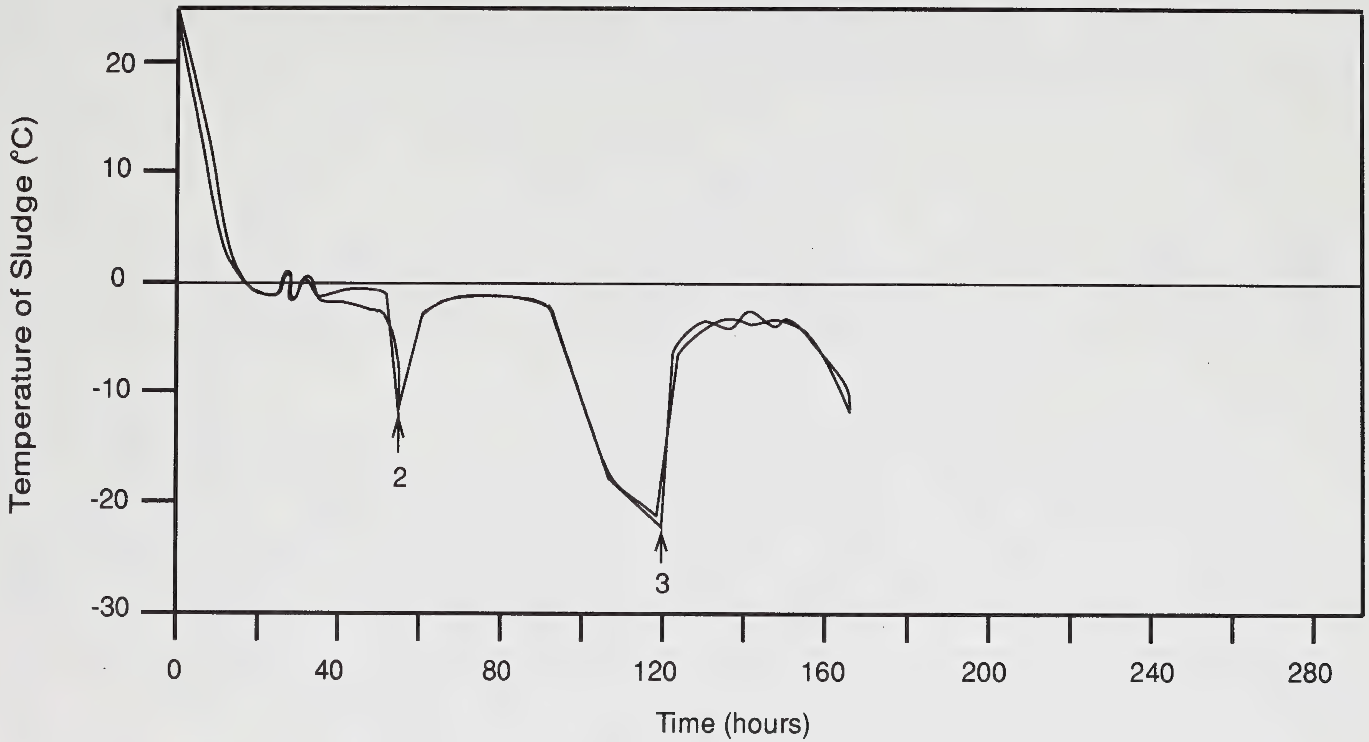


Figure 24. The temperature profile of sludge layer 1 during freezing (as registered by thermocouples 1 and 2) over 180 h. (Arrows indicate the time of adding layers 2 and 3).

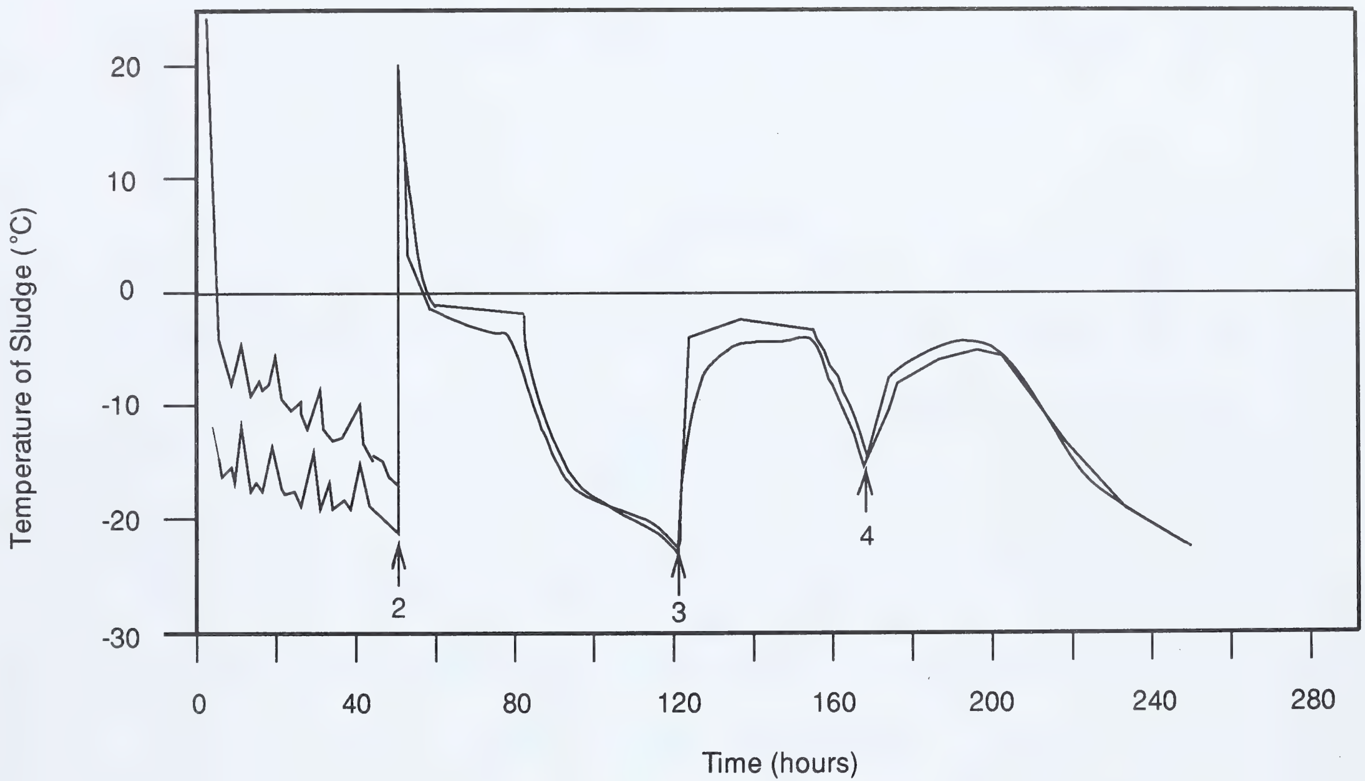


Figure 25. The temperature profile of sludge layer 2 during freezing (as registered by thermocouples 3 and 4) over 260 h. (Arrows 2, 3 and 4 indicate the time of adding layers 2, 3 and 4).

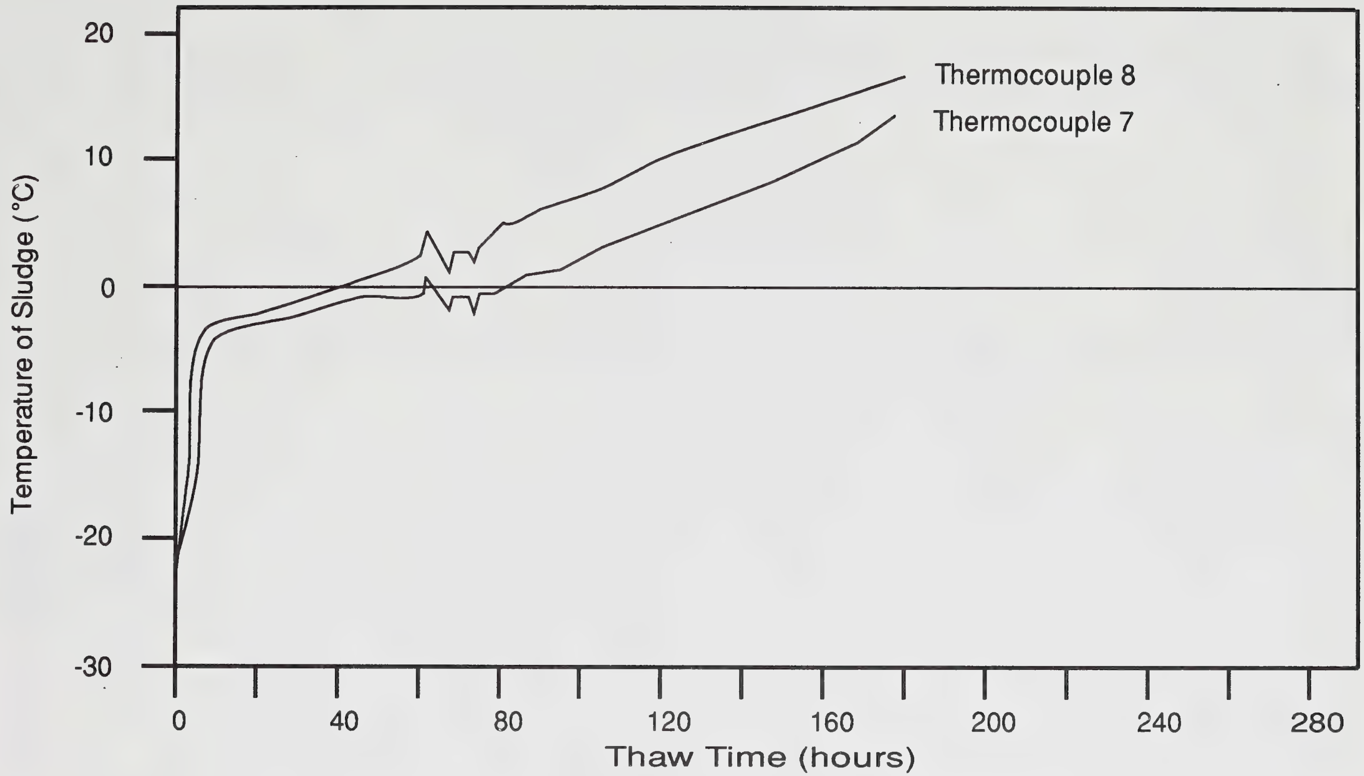


Figure 26. The temperature profile of sludge layer 4 (uppermost) during thaw, as registered by thermocouples 7 and 8, over 190 h.

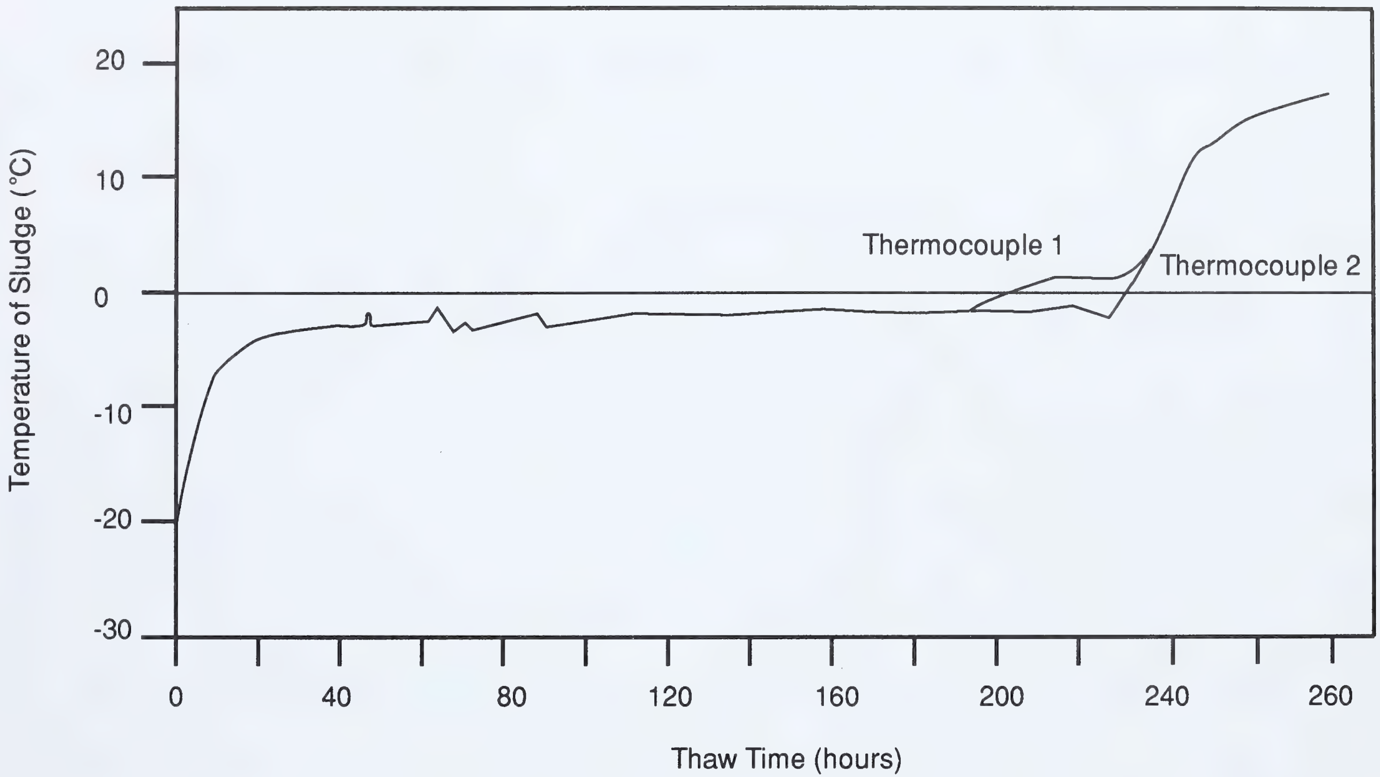


Figure 27. The temperature profile of sludge layer 1 (bottommost) during thaw, as registered by thermocouples 1 and 2, over 300 h.

be faster because the freezing layer would always be on top and uninsulated. The derivative of the Neuman Stefan equation is:

$$\frac{dx}{dt} = \frac{m}{\sqrt{t}} \qquad (\textit{Equation } 15)$$

where

x = depth of freezing (cm)

m = proportionality coefficient

t = time period, days

which shows clearly that as time increases, the rate of freezing decreases (Section 5.3). However, an approximation of freezing times for 46 cm of sludge from both experiments shows that static freezing took 268 h and layered freezing 267 h. There was no difference in freezing time.

Temperature transfer between layers of sludge in layered freezing led to an unexpected phenomenon: when a new layer of warm (room temperature) sludge was added to the surface, the entire mass (to a maximum depth of 46 cm) absorbed the heat and equilibrated to a new increased temperature (-3°C to -7°C depending on the depth of the layer) before dropping in temperature again. Most of the heat added in the new sludge was transferred rapidly into the frozen sludge rather than radiated immediately into the atmosphere. The result was a long freezing time for the 46 cm of sludge as a whole.

It might be that the increase in dewatering under conditions of layered freezing was caused by the repeated temperature fluctuations resulting from adding layers.

The layered freezing experiment showed again that sludge decreases in temperature rapidly to just below 0°C, but the sludge stays at that temperature for a long period of time (20 to 40 h) until the latent heat of fusion is lost. Then, the sludge temperature drops quickly to ambient levels (-24°C in this case). The same phenomenon was observed under conditions of static freezing (Section 5.3).

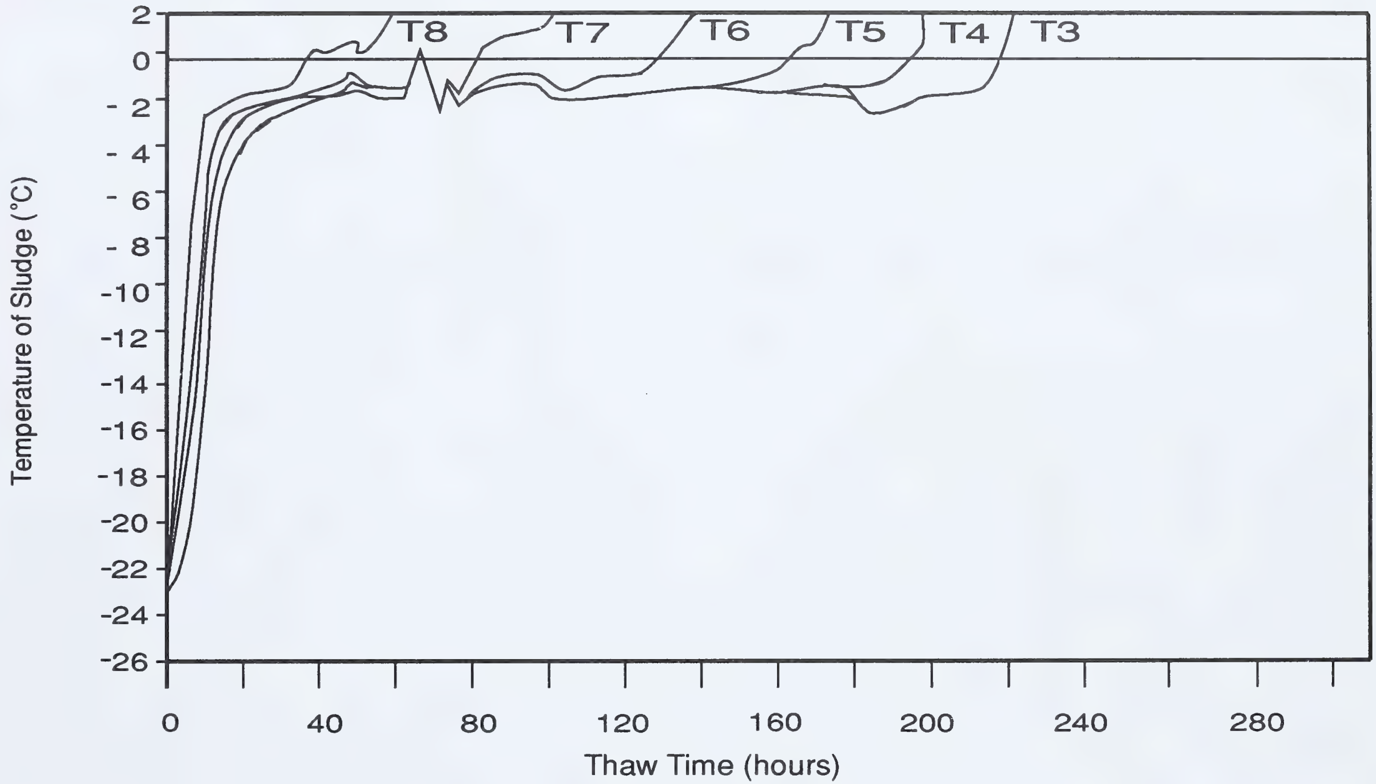


Figure 28. A comparison of temperature profiles during thaw of the upper three sludge layers.

Table 30. A comparison of the effects of two freeze-thaw regimes on solids content and volume reduction in oil sands sludge.

Property	Kind of freeze-thaw system	
	Static	Layered
Initial solids content (%)	25	25
Final solids content (%)	38.7	46.4
Increase in solids (%)	13.7	19.4
Volume reduction (%)	44	49

The thaw process was precisely the inverse: the frozen sludge at very cold temperatures (-24°C) increased quickly to -1°C when warmed, but remained just below 0°C until the latent heat of fusion was replaced, and, then, the temperature rose rapidly to room conditions. The consequences and implications to sludge dewatering of the release and capture of large amounts of energy while water is changing state have not been elucidated. These are purely empirical observations to date.

One of the potential drawbacks of increasing the depth of sludge frozen in the winter is the uncertainty of thaw in the spring and summer. If the bottommost layers of sludge never thawed, a permafrost condition would result. However, the calculation of thaw times in this experiment indicate that even great depths of sludge, say 5 m, will thaw in one summer. At 5 h/cm sludge, 5 m would need approximately 100 days of warm temperatures to thaw completely. Fort McMurray, even at latitude 57° north, enjoys these minimal conditions.

Sludge dewatering by layered freeze-thaw only requires a cold climate. Sludge could be pumped from the bottom of the tailings pond to the surface. A compromise between practicality and economic feasibility would determine the number and the depth of layers to be applied.

The physico-chemical mechanism, which caused larger volume reductions and greater increases in solids for layered freezing compared to static freezing, was not

determined from this experiment. No stress or permeability measurements were taken. Freezing in layers, as opposed to static freezing, may have changed the thermal conductivity of the sludge. The layered freezing may have had a higher increase in solids simply because the entire system (four layers in one barrel) underwent repeated freeze-thaw cycles with each new layer deposited on the surface. Further investigations are required to determine the optimum thickness of layers.

5.5 SURFACE DRAINAGE OF OIL SANDS SLUDGE: SLOPE STABILITY AND SOLIDS CONTENT

One requirement for sludge dewatering is the removal of accumulated water from the sludge surface. Surface water may result from precipitation or be expressed from the sludge during natural consolidation. Regardless of its origin, this water must be removed from the entire drying area to maximize evapotranspiration and to promote stabilization of the sludge surface.

A convenient means of providing surface water drainage would be to form a stable, continuous slope on the sludge as it is poured into a confined area. This would allow the water to be collected and conducted away for treatment.

The objective of this experiment was to relate the solids content of the sludge to the stability of the slope which could be established after deposition in a confined area. A direct measurement of slope stability was performed using a slope table apparatus. An indirect measurement of slope stability assumed that sludge "pourability", or viscosity, was the critical parameter. Because of their high water contents, sludges have very low internal effective stresses. Therefore, the only shear strength involved may be estimated from the rheologic properties of the soil-water mixtures. As McRoberts and Morgenstern (1974) point out: "It is clear that a soil mass, especially at low effective stress conditions, and in a state of limiting equilibrium, will exhibit some form of rate dependent, or viscous, shear strength response". They caution that this approach is useful only in predicting gross movements of flow landslides.

Apparent viscosities of sludges were measured and related to slope stability observations. Thus, a secondary objective was to evaluate viscosity measurements as a method for predicting slope stability.

5.5.1 Materials and Methods

The solids contents of pure sludges were adjusted to range from 30% to 40% (dry weight basis) in increments of 2.5%. Sludge containing approximately 35% solids was available from a lot obtained from the Syncrude tailings pond in the fall of 1986. Sludge containing approximately 50% solids was obtained from the freeze-thaw dewatering experiments. The required range of solids contents (30% to 40%) was prepared by diluting sludges of higher solids contents with water which had been collected from consolidating sludges of the same origin. Solids contents were determined by oven-drying samples at 110°C. A laboratory mixer with an impeller was used to ensure homogeneity of the sludge dilutions.

The slope table apparatus consisted of six acrylic trays cemented together and placed on a flat table. A 2% slope was introduced by placing shims under one end of the trays, as shown in Figure 29. Four kilograms of sludge were introduced from the elevated end of each of five trays, and the poured slope was measured by checking the height difference between the sludge surface and a reference bridge placed end-to-end across each tray (see Figure 30). This technique allowed measurements to be taken several centimetres from any tray boundary. Heights were recorded to the nearest 0.005 cm using a vernier caliper.

All the height differences obtained for sludges were subtracted from those obtained using pure water, which was poured into the sixth tray. In this way, a correction was applied for deflections and irregularities of the apparatus.

The apparent slope was calculated according to:

$$Slope = \frac{(Hw_1 - Hw_2) - (Hs_1 - Hs_2)}{30} \times 100\% \qquad (Equation\ 16)$$

where

Hw and Hs = distances to the water and sludge surfaces, respectively.

Measurements were taken immediately after pouring, after 1 h, and after 3 days. The average of these measurements was reported.

On the third day after pouring the sludges, rainfall was simulated by shaking approximately 1 L of water onto each tray from a jar with a perforated lid. This simulated a fast rainfall of about 9.4 mm in 2 min. Water was then drawn off the low end of each cell using a syringe, and the slope measurements were repeated.

A Brookfield L.V.F. viscometer was used to determine apparent viscosities. Spindle size and rotational speed were selected so that one combination would allow a measurable meter reading for all the sludges being tested. Spindle #3 and a rotational speed of 6 rpm (0.63/s) were used. Temperature was monitored and reported to the nearest 0.5°C. Five-minute trials were performed with readings taken initially and at 1-min intervals. The maximum reading obtained during each 5-min trial was selected for evaluation as an index of shear strength.

5.5.2 Results

Table 31 shows the apparent slope measurements in each tray at various times after pouring. If flow continued over a period of time, consecutive measurements of slope would be expected to decrease. Slopes on sludges with 35% and 40% solids content (Table 31) indicate that this trend was not always obvious. This was because measurements were not all taken at exactly the same locations, and the sludge surfaces had local irregularities. An average of the three slope measurements was considered to be most indicative of the established slope.

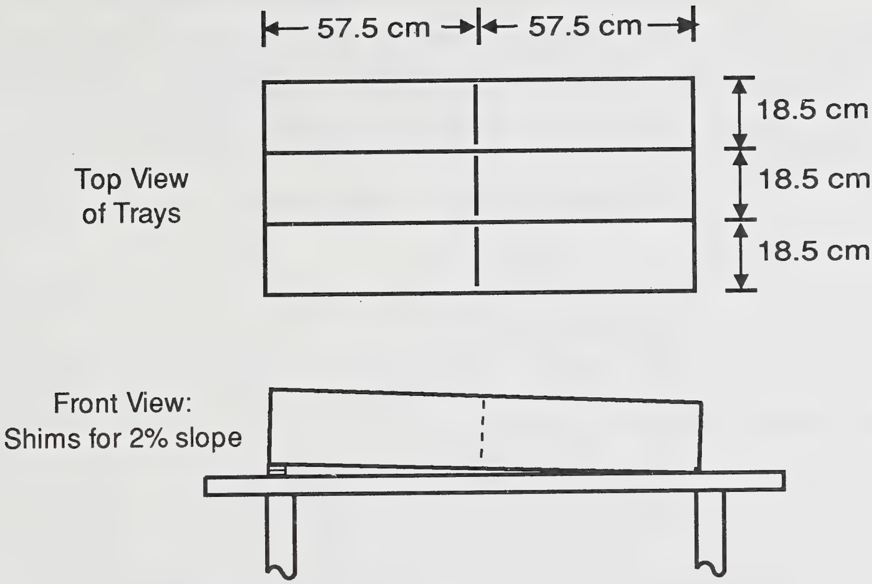


Figure 29. Top and front views of a slope table used to test slope stability.

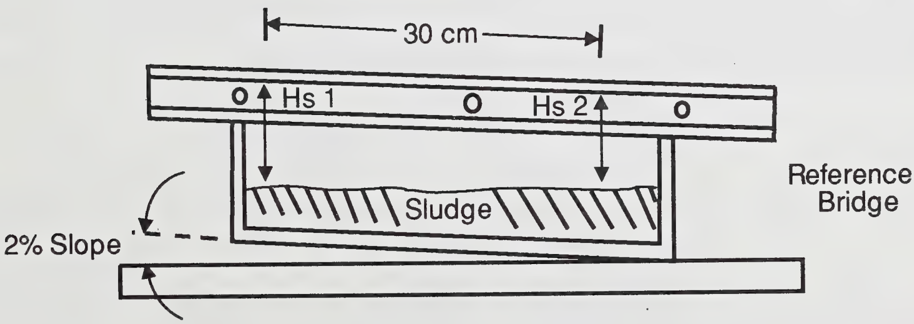


Figure 30. Front view of the slope table with reference bridge.

Figure 31 shows graphically the relationship between solids content and established slope. Note that the graph also compares the remaining slope after simulated rainfall to the pre-rainfall slope. In each case, linear regression was used to draw a best-fit line. The equation of the best-fit line for pre-rainfall data is:

$$S = 44Fs - 12.79 \qquad (\textit{Equation } 17)$$

where

S = established slope in %

Fs = solids fraction

Similarly, the equation for post-rainfall is:

$$S = 44Fs - 13.07 \qquad (\textit{Equation } 18)$$

The data for both graphs indicate a nearly linear relationship between slope stability and solids content. Approximately 34% solids was required to maintain the 2% grade on which the sludge was poured. The best-fit lines are parallel and differ by about 0.3%. Note that an absolute decrease of 0.3% slope nearly destroys the established slope on 30% sludge, but represents a relative decrease of only 6% in the slope on 40% sludge.

The relationship between apparent Brookfield viscosity and the solids content of sludge is non-linear. A linear plot was obtained in Figure 32 by using a semi-logarithmic grid. The equation obtained from the plot is:

$$\mu = e^{23.747}Fs + 2659 \qquad (\textit{Equation } 19)$$

where

μ = apparent viscosity incentipoise

Fs = the solids faction of the sludge

Information obtained from the graphs of slope stability and viscosity can be combined to obtain an equation relating these two parameters directly.

Table 31. Established slope versus solids content of sludge (n = 3).

Solids content (%)	Slope on pouring (%)	Slope at 1 h (%)	Slope at 3 days (%)	Slope average (%)
30	0.57	0.57	0.45	0.53
32.5	1.58	1.48	1.63	1.56
35	2.20	1.93	2.03	2.05
37.5	4.13	4.42	4.10	4.22
40	4.98	4.78	4.33	4.70

$$S = 1.853\ ln(\mu - 2659) - 12.79 \qquad (\textit{Equation } 20)$$

This equation can be used to predict the slope which can be established by pouring the sludge on a 2% grade for sludge having a measured viscosity, μ, of greater than 2,660 centipoise and a solids content between 30% and 40%.

5.5.3 Discussion

The choice of a 2% grade as a basis for slope table measurements was chosen arbitrarily with larger-scale operations in mind. Smaller grades would be hard to establish uniformly and might contain local areas without slope or with opposite slope, resulting in the pooling of surface water. Larger grades would be costly to establish.

The observation that a solids content of at least 34% is required to maintain a 2% slope is significant because tailings sludge used to date contains less than 30% solids. A stiffening agent or partial dewatering would be required before attempting to establish a slope.

The effect of rainfall on established slopes should be investigated more thoroughly. The tests performed were on slopes which had been undisturbed for 3 days after pouring. The effect of rainfall on slopes at various times after pouring and the effects of different quantities and intensities of rainfall should be tested.

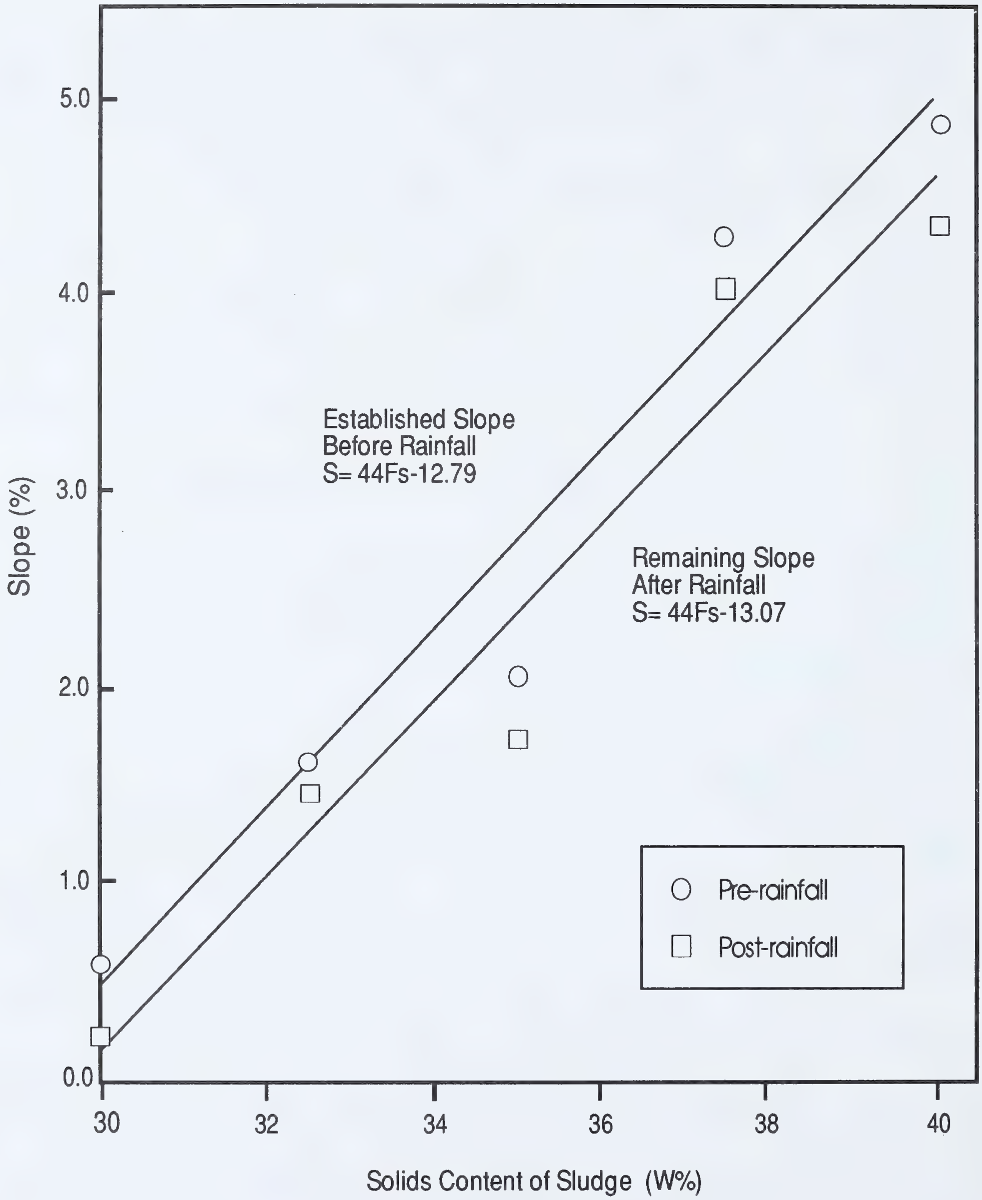


Figure 31. Slope stability before and after rainfall versus solids content.

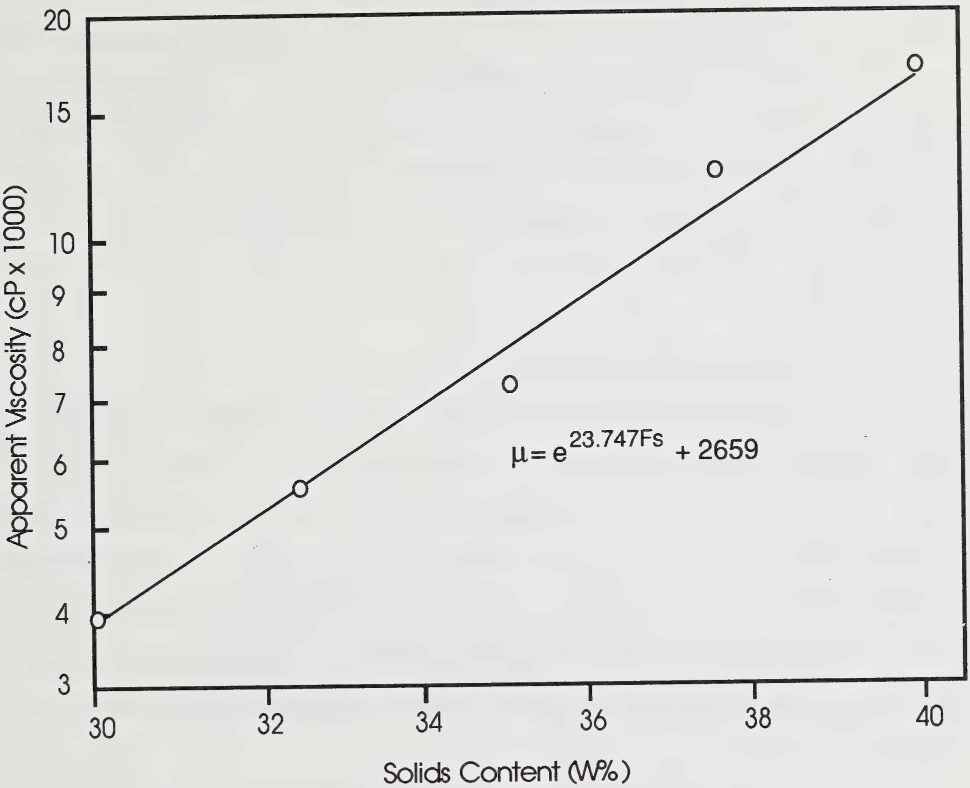


Figure 32. Relationship between viscosity and solids content of sludge.

Slope-stability considerations for large ponds subject to seasonal freeze-thaw cycles are beyond the scope of this investigation, but would become important if slopes were required for long-term surface water drainage. McRoberts and Morgenstern (1974) have prepared an excellent summary and analysis of the various models and mechanisms which have been used to evaluate the stability of thawing slopes.

5.6 SURFACE DRAINAGE OF OIL SANDS SLUDGE: SLOPE STABILITY AND LIME CONCENTRATION

This experiment examined the slope stability that can be obtained by pouring 30% sludge of various lime concentrations into a confined area. Direct measurements of slope stability were made using a slope table apparatus. A secondary objective was to relate slope stability to viscosity measurements.

5.6.1 Materials and Methods

Sludge of 30% solids was prepared by diluting sludge of 35% solids. Water expressed from a sludge of similar origin was used for dilutions. Solids-content determinations were performed by drying samples in an oven at 110°C. Four kilograms of sludge were prepared for each slope table cell. Lime additions were weighed on a laboratory balance to the nearest 0.01 g. The lime, $Ca(OH)_2$, was slowly stirred into the mixing vessel using an impeller-type stirrer to ensure homogeneity. Six mixes were prepared with lime concentrations ranging from 0 ppm to 1,250 ppm in increments of 250 ppm.

The slope table apparatus is shown in Figures 29 and 30 (Section 5.5). The same procedure described in Section 5.5.1 was followed, except that height measurements were taken relative to the top of the cell walls rather than from a bridge. Also, the entire cell length, rather than 30 cm, was used as a basis for calculating slopes. Measurements were taken immediately after pouring. The average of three measurements was reported.

Rainfall corresponding to 9.4 mm in 2 min was simulated as described in Section 5.5.1. Post-rainfall measurements made use of the bridge and a 30 cm span to overcome irregularities caused by erosion near the cell edges. Measurements were made 2 days after the simulated rainfall.

A Brookfield L.V.F. viscometer was used to determine apparent viscosities. Throughout the investigation, spindle #3 and a rotational speed of 6 rpm (0.63/s) were used. This allowed one setting to be used for all the sludges being tested. Temperature was monitored and reported to the nearest 0.5°C. Ten-minute trials were performed with

readings taken initially and at 1-min intervals. To facilitate comparisons, maximum readings were selected. Where the maximum apparent viscosity was the first reading and a continuous decrease with time was obvious, an extrapolation of the plot of apparent viscosity versus time back to time zero was used to estimate the maximum value. The maximum apparent viscosities were used as an index of shear strength.

5.6.2 Results

The effect of lime concentration on slope, where measurements were taken before and after simulated rainfall, are shown in Figure 33. Note that the stabilizing effect of lime additions was not apparent in lime concentrations of less than 500 ppm. Slope stability dipped to a minimum at 500 ppm, but increased at a more than linear rate for further additions of lime up to 1,250 ppm.

The pre-rainfall data indicate that a lime concentration of approximately 950 ppm was necessary to establish the 2% grade on which the samples were poured. The post-rainfall curve indicates that over 1,200 ppm were necessary to maintain this grade.

The pre-rainfall curve of Figure 33 is relatively uniform for lime concentrations above 500 ppm. An equation relating slope stability to lime concentration was obtained by applying linear regression to a plot of 1n(slope) versus lime concentration.

$$\ln S = 1.95\times10^{-3}C - 1.111 \qquad (\textit{Equation } 21)$$

where

S = established slope in %

C = lime concentration in ppm, ($500 \leq C \leq 1{,}250$).

As shown in Figure 34, apparent viscosity increased slightly with an addition of 250 ppm lime and then dipped to a minimum at 500 ppm. Further additions of lime caused sharp increases in viscosity which levelled off before 1,250 ppm were reached. An addition of 1,000 ppm doubled the apparent viscosity of unlimed sludge.

By plotting 1n(viscosity) versus lime concentration and applying linear regression, an equation was determined relating viscosity to lime concentration above 500 ppm.

$$\ln\mu = 1.24\times10^{-3}C + 7.656 \qquad (\textit{Equation } 22)$$

where

μ = apparent viscosity in centipoise

C = lime concentration in ppm, ($500 \leq C \leq 1{,}250$)

A comparison of Figures 33 and 34 shows that both curves have a minimum corresponding to 500 ppm lime. A rapid increase in slope stability and viscosity was apparent as lime concentration went from 500 ppm to 1,250 ppm. However, the viscosity did not level off at 1,250 ppm on the slope-stability curve.

Using the equations relating slope stability and viscosity to lime concentration, a direct relationship between viscosity measurements and slope stability was derived.

$$S = 1.94\times10^{-6}\mu^{1.573} \qquad (\textit{Equation } 23)$$

where

S = slope stability in percent

μ = apparent viscosity, centipoise

The relationship is valid only for 30% sludge with lime concentrations between 500 ppm and 1,250 ppm.

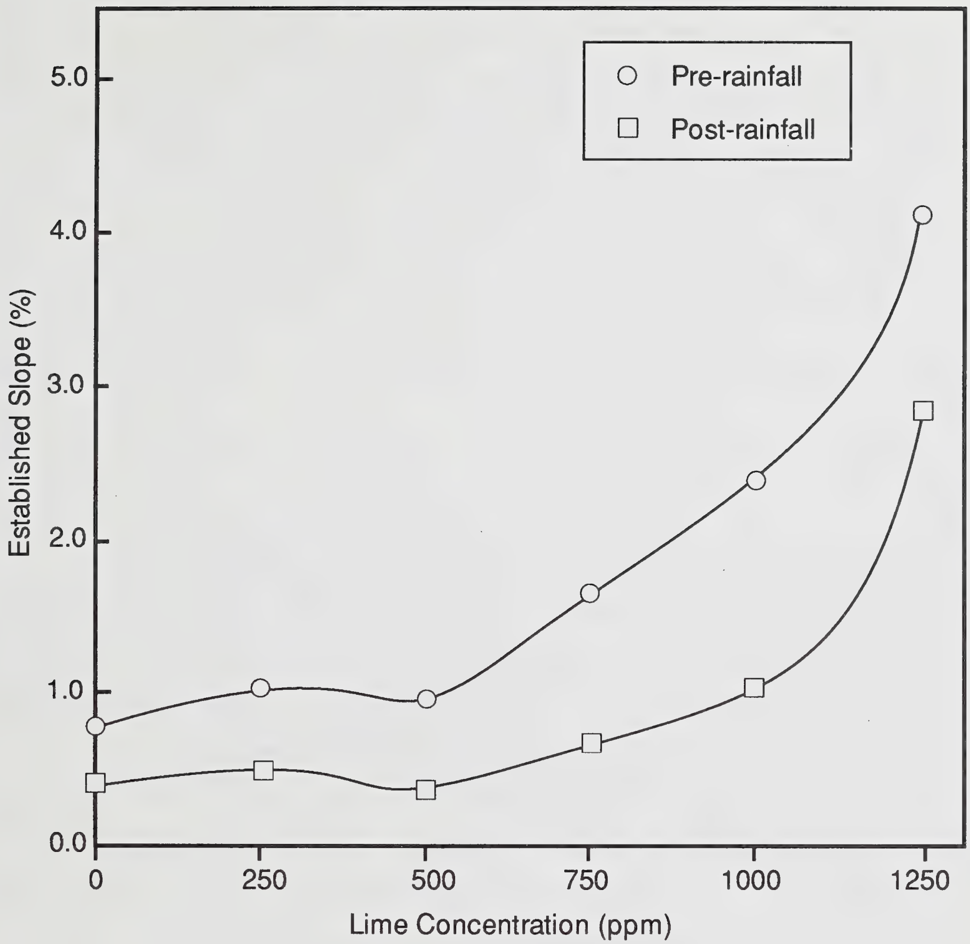


Figure 33. Comparison of slope stability before and after rainfall.

5.6.3 Discussion

Sludge of 30% solids was used in this investigation for two reasons:

1. preliminary investigations showed that it had little slope stability without amendment or other treatment; and
2. it is representative of the solids content of sludge removed to date from the tailings ponds.

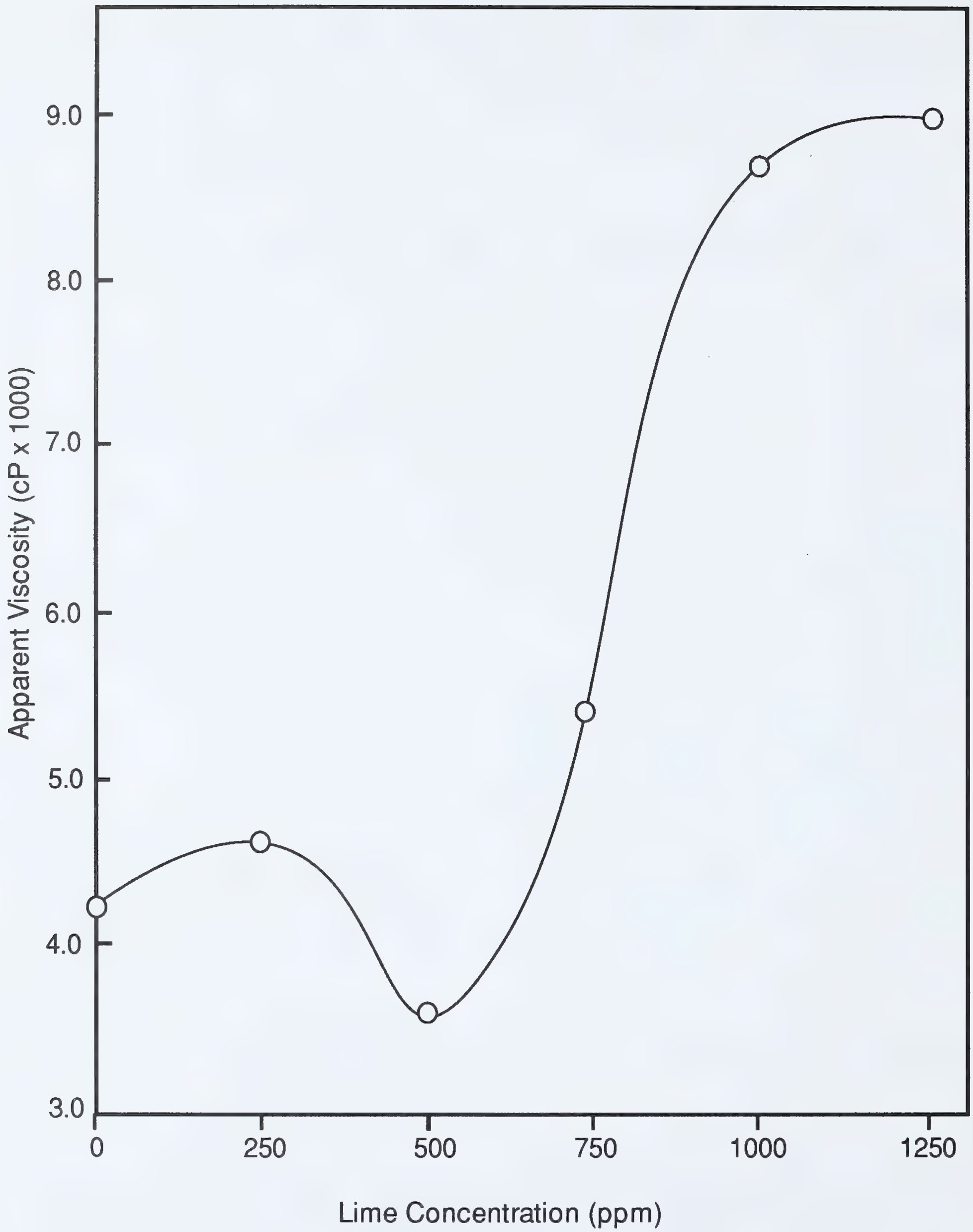


Figure 34. Brookfield viscosity versus lime concentration in 30% sludge.

The observation that a relatively high concentration of lime (950 ppm) is required to maintain a 2% grade could mean that this procedure is not cost effective for large-scale operations. Another consideration would be the cost of mixing. Preliminary trials showed that homogeneity of the mixes was crucial for slope stability.

It was also observed that the measured viscosity decreased over time. Sludge with a relatively high lime concentration and viscosity had a significantly reduced viscosity when restirred and remeasured a few days later. If confirmed, this could mean that the stabilizing effect of lime is too short-lived to be reliable for establishing slopes.

5.7 SURFACE DRAINAGE OF OIL SANDS SLUDGE: INDUCING NATURAL SLOPES AFTER FREEZE-THAW

The objective of this experiment was to identify a practical method for establishing slopes on the surface of sludge after one freeze-thaw cycle. These slopes are needed to drain surface water from the sludge immediately after thawing and during summer rainfall events.

Six unreplicated trials were conducted in the period between July through September, 1987. Trials 1 and 2 were performed to test the suitability of polyethylene as the experimental container as well as to compare the effect of insulated and non-insulated models on freezing and thawing actions. It was hypothesized that insulation would simulate actual conditions by allowing thermal penetration only from the top. Trials 3 and 4 were run to test the effects of sand surcharges and subcharges on surface slope formation. Once it was shown that these sand-sludge configurations were conducive to slope formation, Trials 5 and 6 were performed to examine the extent of sludge dewatering using these configurations.

5.7.1 Materials and Methods

The analysis of solids content was performed on all trials before and after freezing and thawing. From 50 g to 150 g of sludge were oven-dried at 130°C, and results are reported on a dry weight basis.

The polyethylene containers used in Trials 1 and 2 were 63.5-cm square and 41.9-cm deep. The container used in Trial 1 was not insulated. The one used in Trial 2 was externally insulated on the bottom and on all sides with 5.1-cm R10 Styrofoam SM insulation. Plastic drain tubes were installed and connected to pails to monitor the amount of water drained during the thawing process. Thermistors were placed inside the containers at three depths (top, middle, and bottom) to determine the freezing rate of the samples and to establish the time required to freeze all the sludge. A 7.6-cm thick sand dyke was frozen in place at one end of the container before the sludge was added to prevent slumping of the sand into the fresh sludge. After the sludge had frozen, the containers were moved outside to thaw. To prevent rain from disturbing the trials, a roof-shelter without walls was placed over the experiment. During freezing and thawing, a CR21 Micrologger (Campbell Scientific Inc., Vancouver) recorded temperature data from the thermistors.

Trials 3 and 4 used insulated containers like that in Trial 2. Neither Trial 3 nor 4 had a sand dyke. In Trial 3, sand was placed in the bottom of the container before the sludge was poured (Figure 35). In Trial 4, a sand surcharge was placed on top of a frozen sludge layer (Figure 35). In both trials, thermocouples were installed to determine when freezing and thawing were completed. After freezing was complete, the containers were moved outside under the shelter for the thaw cycle. Water was siphoned off the surface in both trials; in fact, this was the sole drainage method performed on Trial 4, the surcharge model.

Trials 5 and 6 extended the methodology of Trials 3 and 4. The configurations are shown in Figure 36. In Trial 5, five thermocouples were installed to monitor temperatures (Figure 36); the sand on the bottom and dyke were frozen in place before the sludge was poured. In Trial 6, the surcharge was added after freezing was completed. In both trials, the plastic drainage tubes were sealed with silicon into the container openings and had non-woven, polypropylene-geotextile cloth stretched over the drainage openings to prevent solids from plugging the drain.

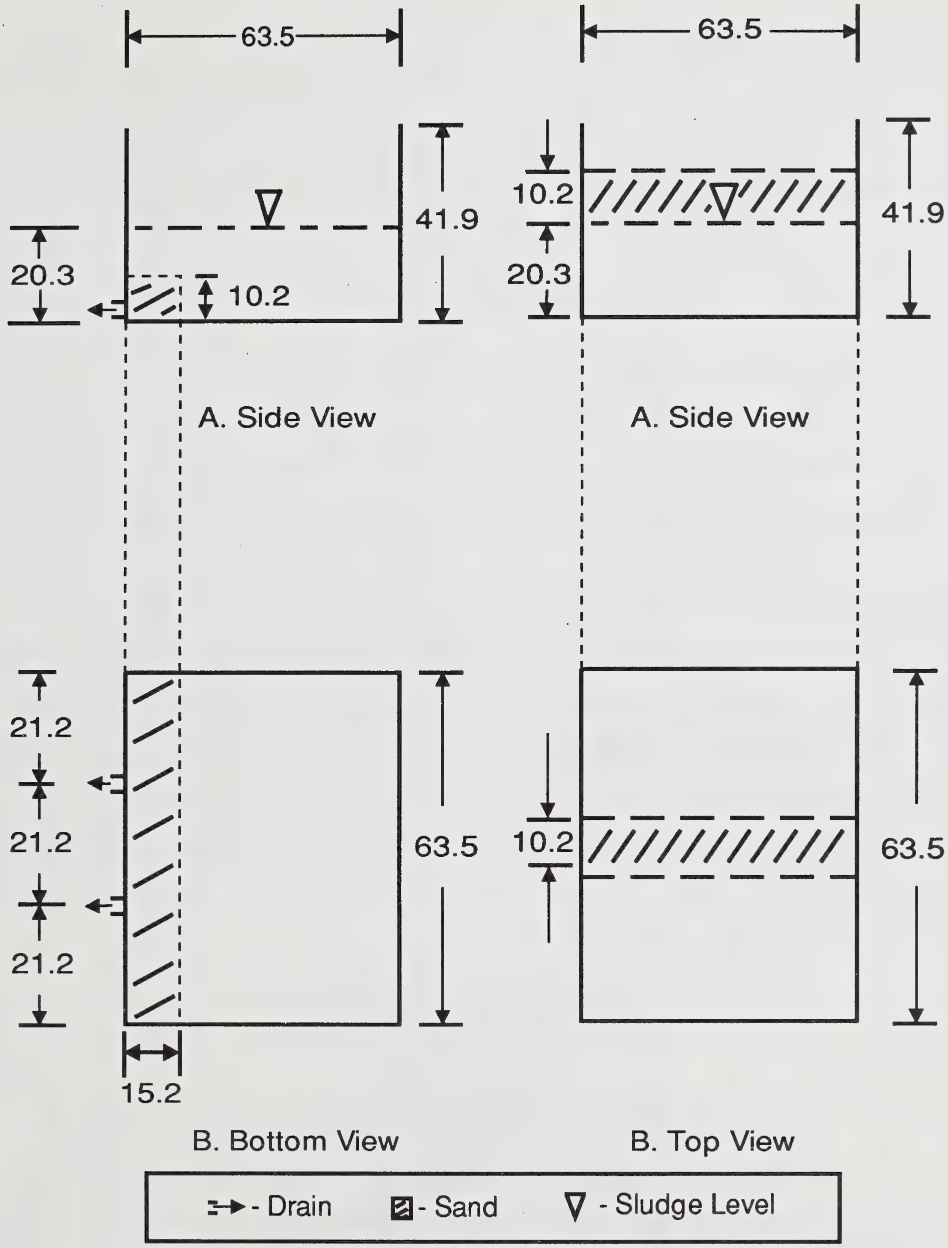


Figure 35. Configuration of Trial 3 (sand on bottom) and Trial 4 (sand surcharge) before freezing and thawing (all dimensions in cm).

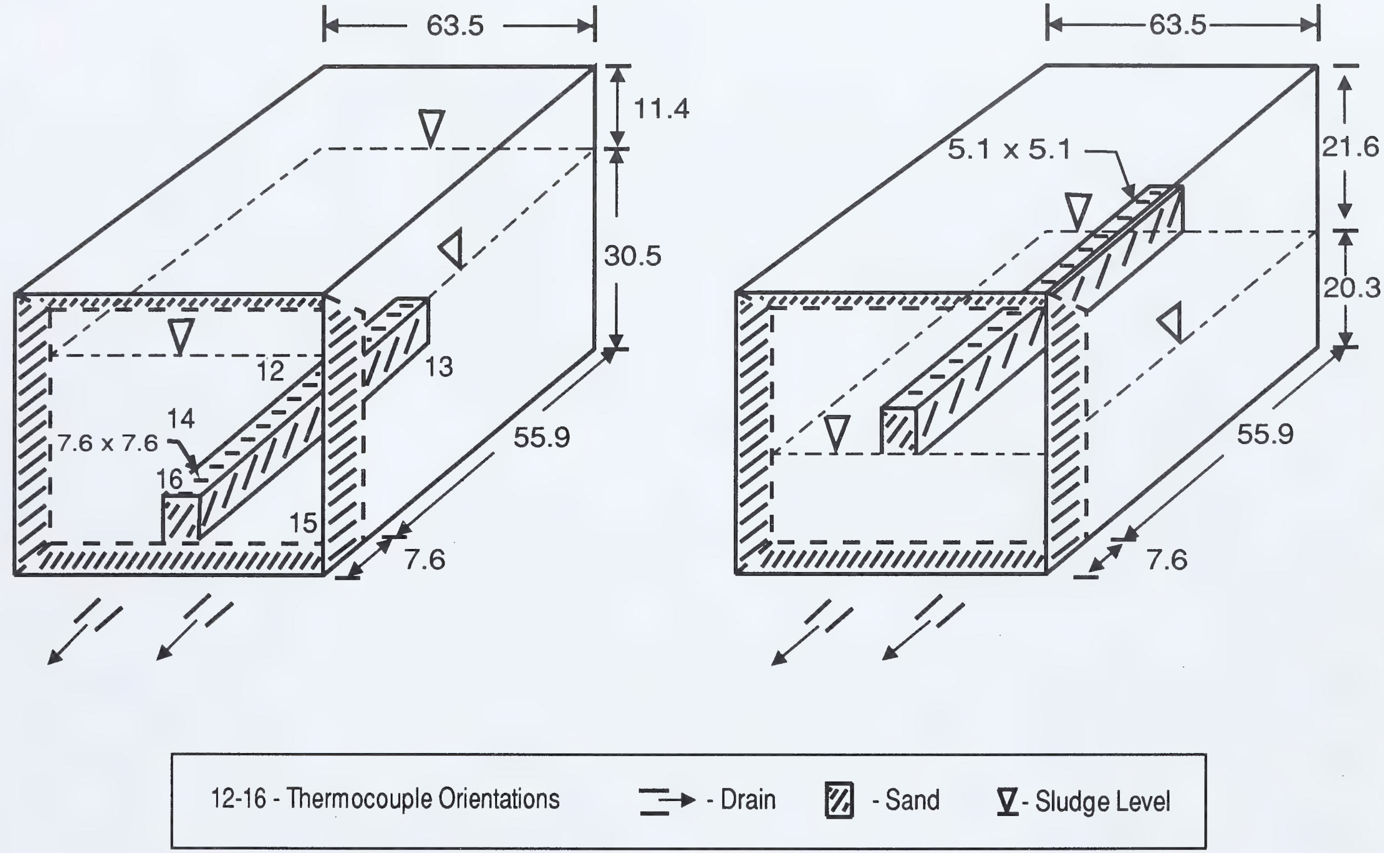


Figure 36. Configuration of Trial 5 (sand on bottom) and Trial 6 (sand surcharge) before freezing and thawing (all dimensions in cm).

The sludge used in all six trials was obtained in 1986 from Syncrude Canada Ltd. from the mature sludge layer of the tailings pond. The average freezer temperature during the freezing cycle of each trial was -24°C. To calculate the reduction in sludge owing to freezing and thawing in Trials 1, 2, 5, and 6, initial sludge volumes and the amounts of moisture recovered by drainage were measured.

5.7.2 Results

The effect of freeze-thaw on percent solids concentration of oil sands sludge is summarized in Table 32. A comparison of Trials 1 and 2 reveals an approximate 1.4 times greater increase in solids content for the non-insulated sample relative to the insulated sample. Trials involving different sand configurations produced an average increase of 25% solids.

The time taken for the non-insulated sample in Trial 1 to freeze was 3 days shorter than that for the insulated sample in Trial 2. The non-insulated sample also had a rapid increase in temperature during the thaw in comparison to the insulated sample. Freezing rates were calculated from freezing curves generated from temperature data for the top thermistors of the samples. The maximum freezing rate corresponded to readings of the uppermost thermistor in Trial 2, the insulated sample. From the freezing curve in Figure 37, the maximum freezing rate was determined by

$$F_r = \frac{d.L}{(T_2 - T_1)} \qquad \textit{(Equation 24)}$$

where

F_r	=	maximum freezing rate of the sludge (mm/h)
d	=	depth of measurement, 60 mm
L	=	rate of temperature change as determined by the slope of the initial tangent to freezing curve, Figure 37 (°C/h)
T1	=	initial sludge temperature, 26°C
T2	=	sludge freezing temperature, 0°C

Table 32. The solids contents (%) of six sludge trials undergoing freezing and thawing.

Trial	Trial type	% Solids contents[1]		
		Before freeze-thaw	After freeze-thaw	Increase
1	Non-insulated	32.8	56.3	+23.5
2	Insulated, no sand	30.2	46.6	+16.4
3	Sand on bottom	34.4	60.4[2]	+26.0[2]
4	Sand surcharge	34.4	56.2	+21.8
5	Sand on bottom	34.6	59.2	+24.6
6	Sand surcharge	34.6	63.0	+28.4

[1] All reported data are averages of 2 samples taken in the upper and lower sludge layers except trial 3.
[2] Average of two samples from above and adjacent to the subcharge.

Therefore, the maximum freezing rate = 10.71 mm/h.

The volume of moisture recovered in both trials was 60 L. Since the initial volumes of both trials were equal, the volume reduction was also equal. The initial volume was 139.6 L and:

$$V_R = V_m \times \frac{100}{V_I} \qquad \textit{(Equation 25)}$$

where

V_R = volume reduction

V_m = volume of moisture recovered

V_I = initial sludge volume

Therefore, the volume reduction was 43%.

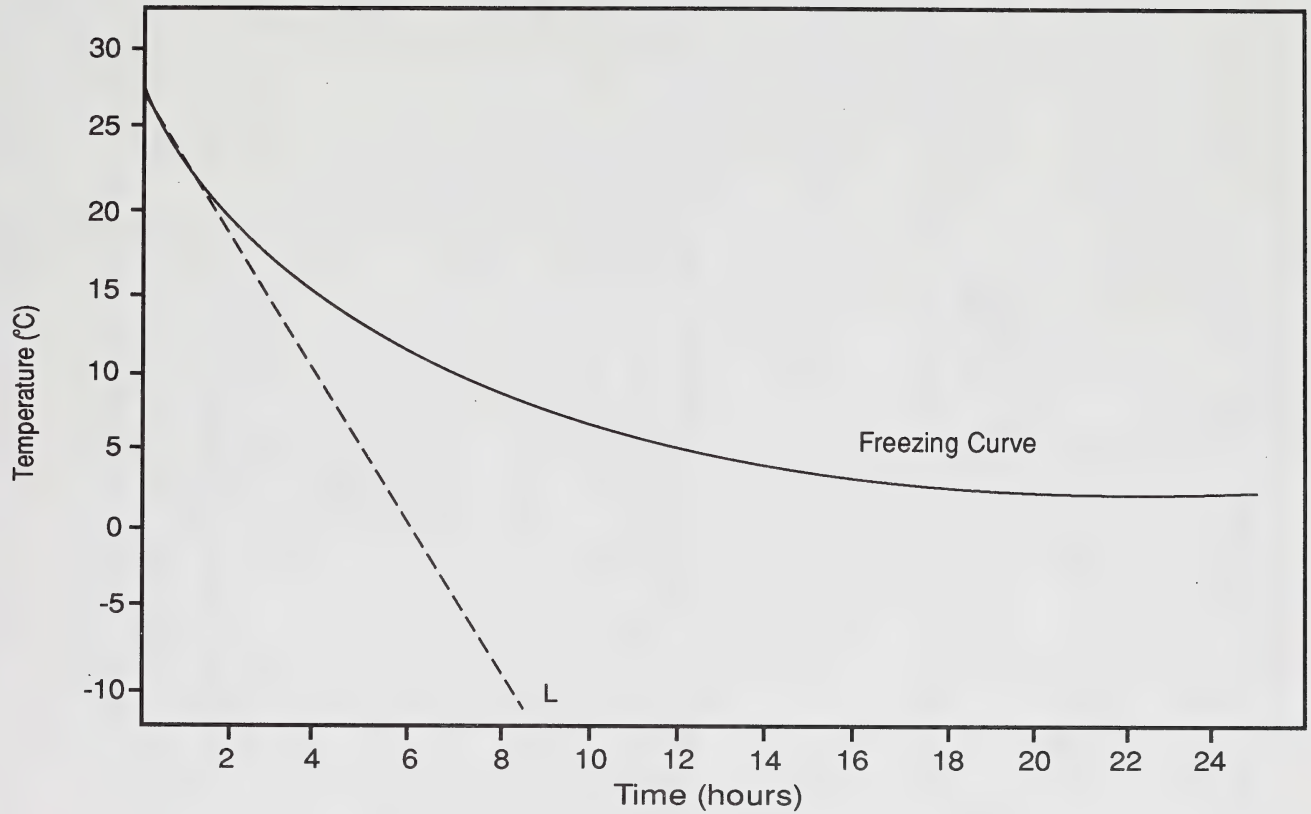


Figure 37. Freezing curve for the top thermistor in Trial 2.

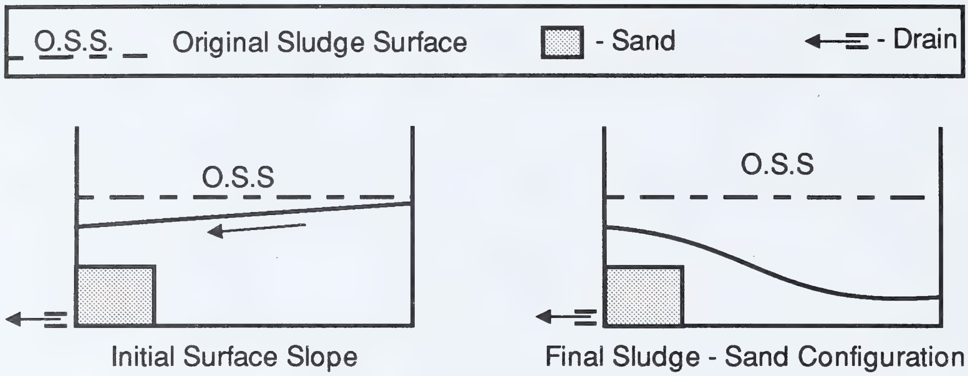


Figure 38. The effect of placing sand on the bottom in configuring the surface slope of oil sands sludge undergoing freezing and thawing (Trial 3, not to scale).

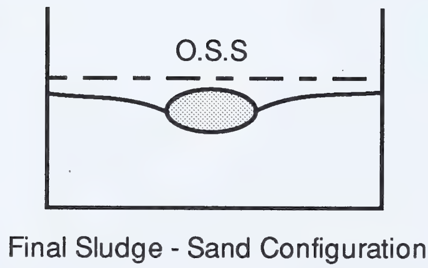


Figure 39. The effect of a sand surcharge in configuring the surface slope of oil sands sludge undergoing freezing and thawing (Trial 4, not to scale).

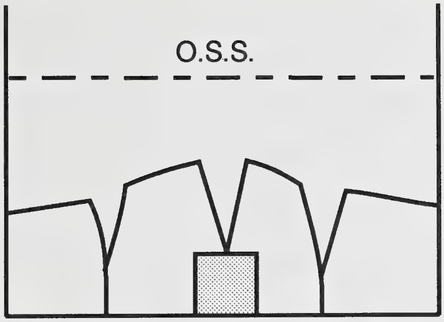


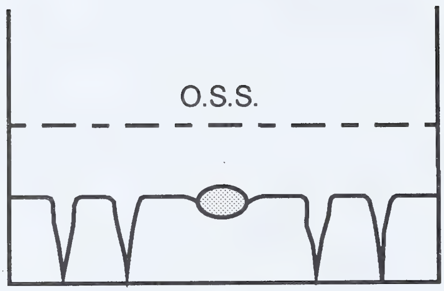
Figure 40. The effect of placing sand on the bottom in configuring the surface slope of oil sands sludge undergoing freezing and thawing (Trial 5 not to scale).

Although the thaw times for the non-insulated and the insulated containers were 3.5 days and 2 days, respectively, this did not account for the large difference in minimum temperatures (non-insulated = -23°C; insulated = -8°C). When Trial 2 was terminated, large ice crystals were found at the bottom of the container, indicating incomplete thawing of the sludge.

The final sludge-sand configuration of Trials 3 and 4 (Figures 38 and 39) indicated that both subcharge and surcharge models caused sloping surfaces and channels necessary for the removal of surface water.

In Trials 5 and 6, the subcharge model provided a large surface deformation consisting of a ridge on top of the subcharge with a declining slope to either side of this ridge (Figure 40). The surcharge model produced a comparatively small surface deformation (Figure 41). A network of large cracks extending to the bottom of the containers and running parallel and perpendicular to the sand was created during dehydration of the sludge.

The volumes of moisture recovered in Trials 5 and 6 were 48 L and 41 L, respectively, resulting in a 45.8% and 56.9% reduction in volume.



A. Final Sludge - Sand Configuration

Figure 41. The effect of a sand surcharge on configuring the surface slope of oil sands sludge undergoing freezing and thawing (Trial 6, not to scale).

5.7.3 <u>Discussion</u>

The results of these trials show that surface drainage is enhanced through the use of sand to configure the surface slopes of oil sand sludges undergoing freezing and thawing. After the surface water was removed, a network of surface cracks was created during further sludge dehydration. These cracks provide channels for bulk water removal and greater surface area for additional dehydration by evaporation.

The dewatering effectiveness of the various drainage systems, combined with the freeze-thaw process, is shown by the increase in the percent solids content of the sludge (Table 32). The insulated model (Trial 2) did not undergo complete thaw and, perhaps, because of this showed a lower increase in percent solids. Subsequent trials using insulated boxes were subjected to longer thawing periods to ensure a complete phase change of the sludge.

In general, the sludge with sand below was drained from the bottom and the top. Therefore, it exhibited a greater increase in solids (compare Trials 3 and 4 in Table 32). In contrast, Trial 5 (sand below) had a smaller percent solids increase than Trial 6 (surcharge). This was probably caused by the larger volume of sludge used in Trial 5 (105 L versus 72 L) over an equal (and relatively short) time span.

From temperature data collected in Trials 1 and 2, the maximum freezing rate of the sludge was calculated to be 10.71 mm/h. Previous work by Logsdon and Edgerley Jr. (1971) on chemically amended sludges suggested that the maximum freezing rate was 20.5 mm/h. Since their rate was not exceeded and temperature differentials used in these trials (-50°C) will not be encountered in the field, flash freezing of the sludge with resultant particle entrapment should not be a problem.

5.8 THE FERTILIZER REQUIREMENTS OF REED CANARY GRASS ON OIL SANDS SLUDGE

The nutrient content of oil sands sludge is low. Plants, such as reed canary grass, need a certain quantity of the major elements to establish and grow. The evapotranspiration and root mass development of any plant will be limited, if sufficient nitrogen, phosphorus, and potassium are not present.

This study of the effect of fertilization on grass growth in oil sands sludge is special in several ways. First, the medium itself--silt and clay mineral particles coated with bitumen and suspended in slightly saline water--is new and unknown. Second, plants have not been grown intentionally on this medium before, and the requirements of reed canary grass are not well known, even on the more common substrates, such as soil or peat. Third, the climate of Fort McMurray is harsh: summers are short, days are long, and temperatures are cool. There has been little fertility work done in climates such as this. Fourth, the economics of biological dewatering using grasses like reed canary grass will depend to a large extent on the amount of fertilizer required. If high concentrations are required, the cost of dewatering 25 million cubic metres of sludge per year will be prohibitive.

The objectives of this experiment were: (1) to determine the optimum fertilizer concentration for reed canary grass to be established and to grow on oil sands sludge; (2) to characterize the loss of nutrient elements in the thaw water that could be expected if the fertilizer were added prior to freezing; and (3) to identify the effect of fertilizer on the increase of solids in oil sands sludge during freezing and thawing.

5.8.1 Materials and Methods

Oil sands sludge from the tailings pond at Mildred Lake (Syncrude Canada Ltd.) was mixed with sufficient water from the same site to yield a final sludge at 32% solids (dry weight basis). The sludge product was then sampled and analyzed for solids content, as well as nitrogen, phosphorus, and potassium content. (See Section 2 for details of analytical procedures).

The sludge was then transferred to 64, 22-L pails where fertilizer treatments were added. Nitrogen was added as 90% urea and 10% magnesium nitrate at 0 ppm, 100 ppm, 200 ppm, and 300 ppm. Phosphorus was added as monobasic potassium phosphate at 0 ppm, 30 ppm, 60 ppm, and 90 ppm-P. Potassium was added in small amounts as monobasic potassium phosphate and supplemented to 0 ppm, 150 ppm, 300 ppm, and 450 ppm-K with potassium sulfate. All possible combinations of fertilizers were included, i.e., three fertilizer nutrients at four levels for a total of 64 combinations.

The sludge-fertilizer combinations were mixed and placed in a freezer at -24°C for 72 h. The frozen sludge was removed and allowed to thaw. The water was decanted from the surface. The decant water from the four treatments, representing no fertilizer (0), a low fertilizer level (100 ppm N, 30 ppm P, 150 ppm K), a medium fertilizer level (200 ppm N, 60 ppm P, 300 ppm K), and a high fertilizer level (300 ppm N, 90 ppm P, 450 ppm K), were analyzed for N, P, and K. The remaining sludge in these same four treatments was mixed again and sampled for solids content. From each of the 64 sludge-fertilizer treatments, three replicates were poured (3-L plastic pails).

Two centimetres of moistened peat moss were mixed with the equivalent of 28 kg/ha reed canary grass seed and placed on the sludge surface. The seeded pails were placed on tables in the Alberta Environmental Centre greenhouse in a randomized complete block design. The greenhouse was maintained at 20°C with a 16-h light period (using supplemental high intensity discharge lights as necessary). The sludge treatments were watered every third day with 117 mm of deionized water to simulate precipitation in Fort McMurray in July.

After the plants had germinated, the pails were thinned to 15 plants/ replicate. Visual observations were made every 2 weeks. After 52 days, the entire above-ground biomass was harvested, dried at 70°C, and weighed (harvest 1). The regrowth of all replicates was harvested, dried at 70°C, and weighed (harvest 2). Total biomass production was the sum of harvests 1 and 2. The experiment was ended after 73 days.

5.8.2 Results

The addition of small or large amounts of fertilizer did not have a notable effect on increasing the solids content of oil sands sludge during freezing and thawing (Table 33). When no fertilizer was added, the freeze-thaw cycle caused the oil sands sludge to increase from 32% to 50.5% solids. Adding fertilizer in three increments--260 ppm, 560 ppm, and 840 ppm--caused a maximum increase of only 0.7% solids over sludge without added fertilizers.

Unamended oil sands sludge had extremely low levels of all three major nutrients: N = 7 ppm, P = 2 ppm, and K = 11 ppm. Nutrients added to oil sands sludge prior to freezing were susceptible to loss in the water drained after the thaw (Figures 42 and 43). Approximately one-half the nitrate-nitrogen added was lost in the thaw water, a relationship which held true across the full range of added nitrate (0 ppm to 30 ppm). Ammonium-nitrogen presented a different picture: at 90 ppm added, 27 ppm were lost; regardless of further additions (up to 270 ppm in Figure 42), no more ammonium was lost

Table 33. The effect of fertilizer addition on the change of solids contents[1] of oil sands sludge during freezing and thawing.

Fertilizer levels	Fertilizer nutrients added			Final solids content[2] (%)	Increase over initial (%)
	N	P	K		
		(ppm)			
None	0	0	0	50.5	18.5
Low	100	30	150	51.0	19.0
Medium	200	60	300	51.2	19.2
High	300	90	450	51.1	19.1

[1] Initial solids contents of all oil sands sludge undergoing freezing and thawing was 32.0% (n = 3).
[2] Non-replicated measurements.

in the water. Like nitrate-N, phosphorus and potassium were lost in proportion to the quantities added prior to freezing, although the relationship for phosphorus was much closer (r^2 = 0.83) than that of potassium (r^2 = 0.51). Slightly less than one-third the added phosphorus and potassium was lost in the thaw water (Figure 43).

Reed canary grass responded to the addition of nutrients to oil sands sludge (solids content = 50%). When no fertilizer was added, the plants lacked vigour, showed early signs of etiolation (yellowing), and grew slowly. With only the first level of each of the nutrient elements added, the growing conditions of the sludge changed enough to promote growth and development.

On the average, the biomass of reed canary grass grown on 50% solids sludge responded more to nitrogen and phosphorus than to potassium (Table 34). Comparing two harvests of reed canary in the same pots, the first produced more biomass than the second in all cases (no statistical analysis was done because there were significant 2-way and 3-way interactions). When no fertilizer of any kind was added to the sludge, the plant production was 0.02 g/pot (average of 9 replicates, data not shown). When no nitrogen was added, total biomass (two harvests) production was low

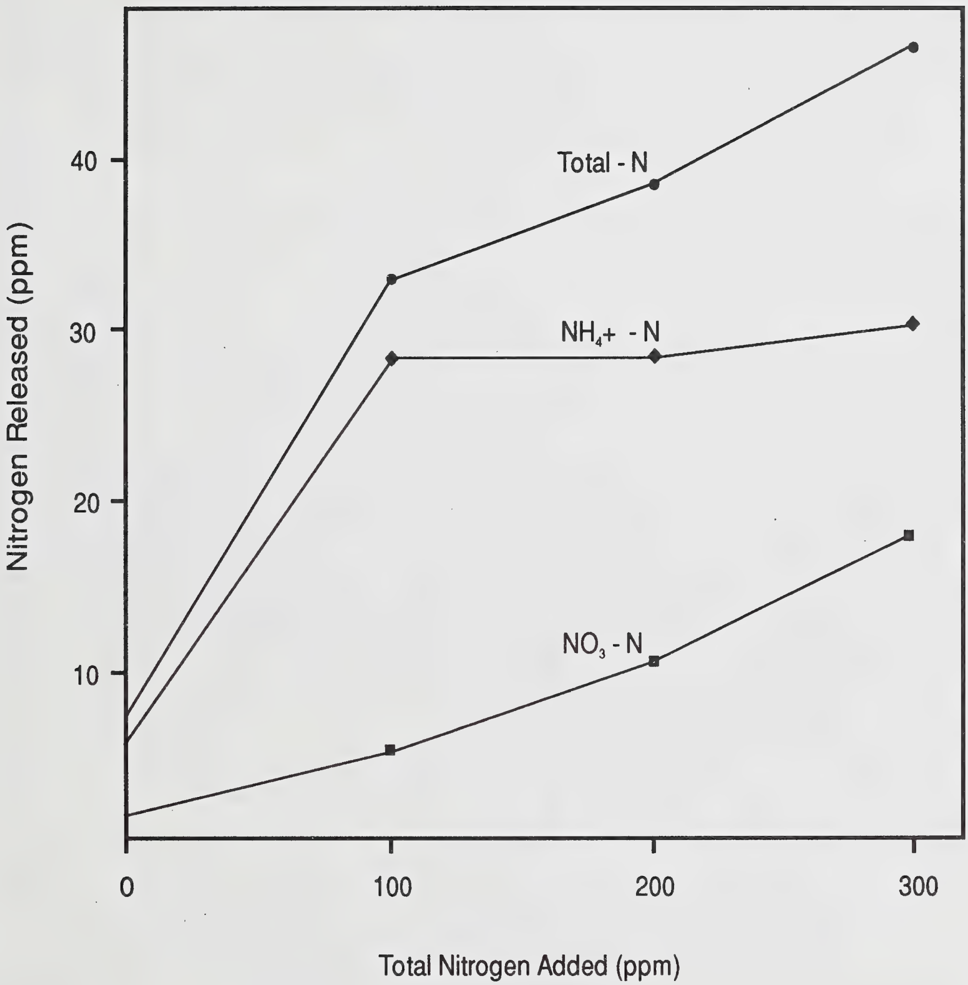


Figure 42. The relationship (non-replicated) between three forms of added and released nitrogen during the process of freezing and thawing oil sands sludge. (Each 100 ppm total nitrogen includes 90 ppm NH_4-N and 10 ppm NO_3-N.)

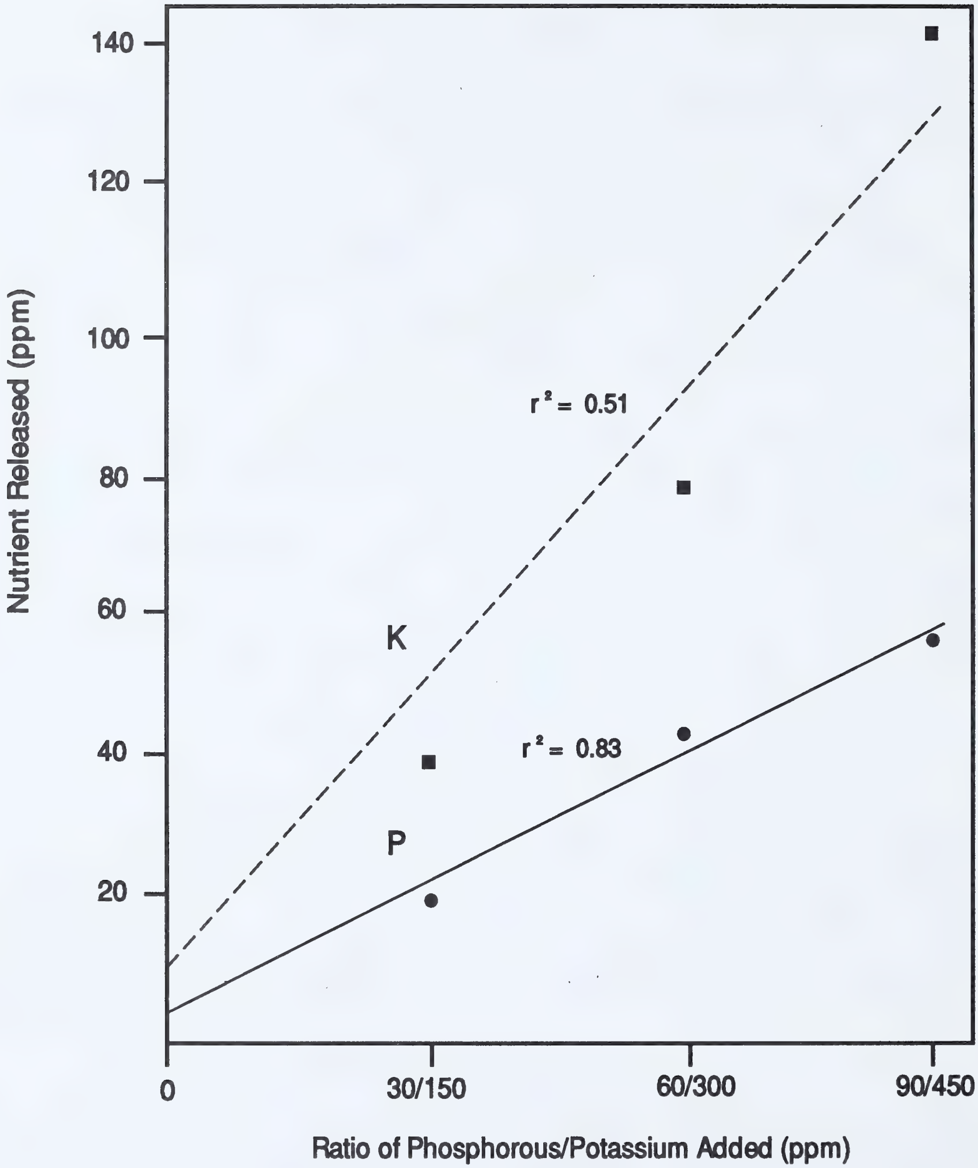


Figure 43. The effect of adding phosphorus (P) or potassium (K) on the release of each during the process of freezing and thawing oil sands sludge (non-replicated).

Table 34. Dry biomass of two harvests of reed canary grass (g/pot) grown on oil sands sludge amended with 3 nutrient elements at 4 levels each (n = 48).

Nutrient Level[1] Added	Nutrient Added								
	Nitrogen			Phosphorus			Potassium		
	[2]H1	H2	T[3]	H1	H2	T	H1	H2	T
0	0.71	0.09	0.80	0.02	0	0.02	1.58	0.74	2.39
1	3.08	0.90	3.98	2.71	1.27	3.98	1.95	0.98	2.93
2	2.69	1.71	4.40	2.68	1.24	3.92	1.90	0.90	2.80
3	0.79	0.81	1.60	1.86	0.99	2.85	1.56	0.88	2.44

[1] Levels of nutrients added are: N0 = 0, N1 = 100 ppm, N2 = 200 ppm, N3 = 300 ppm; P0 = 0, P1 = 30 ppm, P2 = 60 ppm, P3 = 90 ppm; K0 = 0, K1 = 150 ppm, K2 = 300 ppm, K3 = 450 ppm.
[2] H1 was harvest 1 at 52 days; H2 was harvest 2 at 100 days.
[3] T is the total of harvest 1 and harvest 2.

(0.8 g/pot, Table 34); by adding 100 ppm N, total biomass increased to nearly 4 g/pot. When no phosphorus was added, regardless of the level of nitrogen and potassium, the average biomass in the first harvest was also 0.02 g/pot (Table 34). In the absence of phosphorus, the plants did not grow between the first and second harvests (Table 34).

Many of the results noted above for harvests 1 and 2 were confirmed by an analysis of variance of total biomass (Table 35). At the 0.1% level of probability, nitrogen and phosphorus had a significant effect on total biomass production. The nitrogen x phosphorus two-way interaction and nitrogen x phosphorus x potassium three-way interaction were also highly significant. Even the simple effect of potassium, the two-way nitrogen x potassium interaction and phosphorus x potassium interaction were significant at 5% and 1% levels of probability, respectively.

The highly significant interaction of nitrogen x phosphorus is shown in Figure 44. It is easy to see that the lack of phosphorus addition caused a decline in total biomass production of reed canary grass on sludge, regardless of the amount of nitrogen added. The addition of either 30 ppm or 60 ppm-P and 100 ppm-N led to nearly a six-fold increase in biomass. If another 100 ppm-N was added, only the 60 ppm-P treatment responded with more biomass production, and the increase was only 15%. The effect of adding too much nitrogen (300 ppm) was uniform, regardless of the amount of P; all biomass production dropped to approximately the same level as when no nitrogen was added.

Unlike phosphorus, plants without potassium responded greatly to the addition of 100 ppm or 200 ppm-N (Figure 45). There was virtually no difference between 150 ppm, 300 ppm, and 450 ppm-K on reed canary grass biomass production over the full range of nitrogen additions. All three potassium levels caused production to rise 400% from 0 ppm-N to 100 ppm-N; production stayed approximately the same for 200 ppm-N, and dropped off sharply when excess nitrogen (300 ppm) was added.

The phosphorus x potassium interaction was different from the two described above (Figure 46). The plants without phosphorus yielded practically nothing, regardless of the amount of potassium added. The 30 ppm and 60 ppm-P treatments did

Table 35. Analysis of variance (ANOVA) of the effect of three nutrient element (NPK) additions at four levels each and their interactions on total plant biomass production.

Source	df	ANOVA S.S.	F
Nitrogen	3	446.8	160.5***
Phosphorus	3	495.4	178.0***
Potassium	3	9.5	3.4*
Nitrogen x Phosphorus	9	173.8	20.8***
Nitrogen x Potassium	9	18.9	2.3*
Potassium x Phosphorus	9	25.6	3.1**
Nitrogen x Phosphorus x Potassium	27	64.0	2.6***
Replicate	2	1.7	
Error	129	259.5	

* Significant at the 5% level
** Significant at the 1% level
*** Significant at the 0.1% level

not vary significantly with increasing potassium levels. These treatments produced between 3.5 and 4.5 g/pot, regardless of potassium level. Only the 90 ppm-P treatment showed a large increase in biomass production with a change from 0 ppm to 150 ppm-K.

5.8.3 Discussion

Although adding fertilizer did not cause either an increase or a decrease in the solids content of sludge during freezing and thawing, there was a large loss of all added nutrient elements with the release of the thaw water. Approximately one-half the

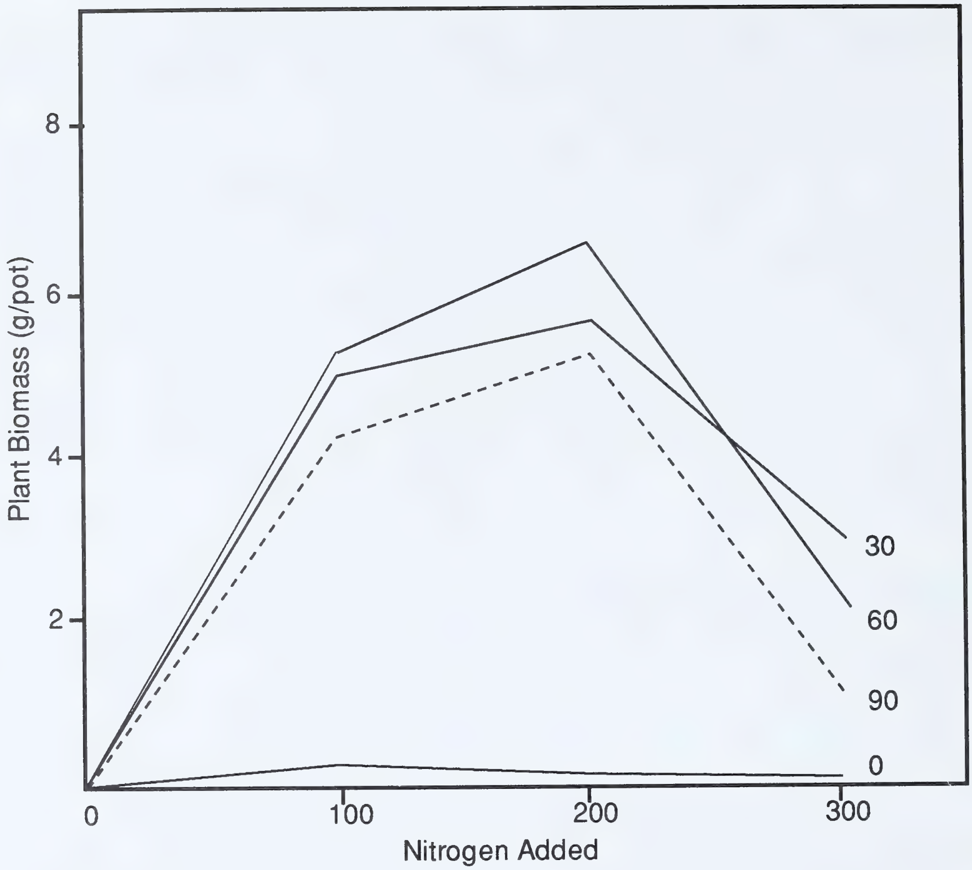


Figure 44. Interaction N x P: The effect of adding nitrogen, at four levels of phosphorus, on the biomass production of reed canary grass on oil sands sludge (n = 12).

added nitrate-nitrogen and one-third the added phosphorus and potassium were lost. Only ammonium-nitrogen remained constant, at 27 ppm released into the thaw water, regardless of the amount added.

The consequences of the magnitude of the release identified here are important to the economic feasibility and environmental acceptability of biological dewatering on a large scale. If one-third to one-half of the added fertilizer drains away with the thaw water, more expensive forms of fertilizer which stay attached to the solids might be used. Another option would be to apply fertilizer after the thaw water has been

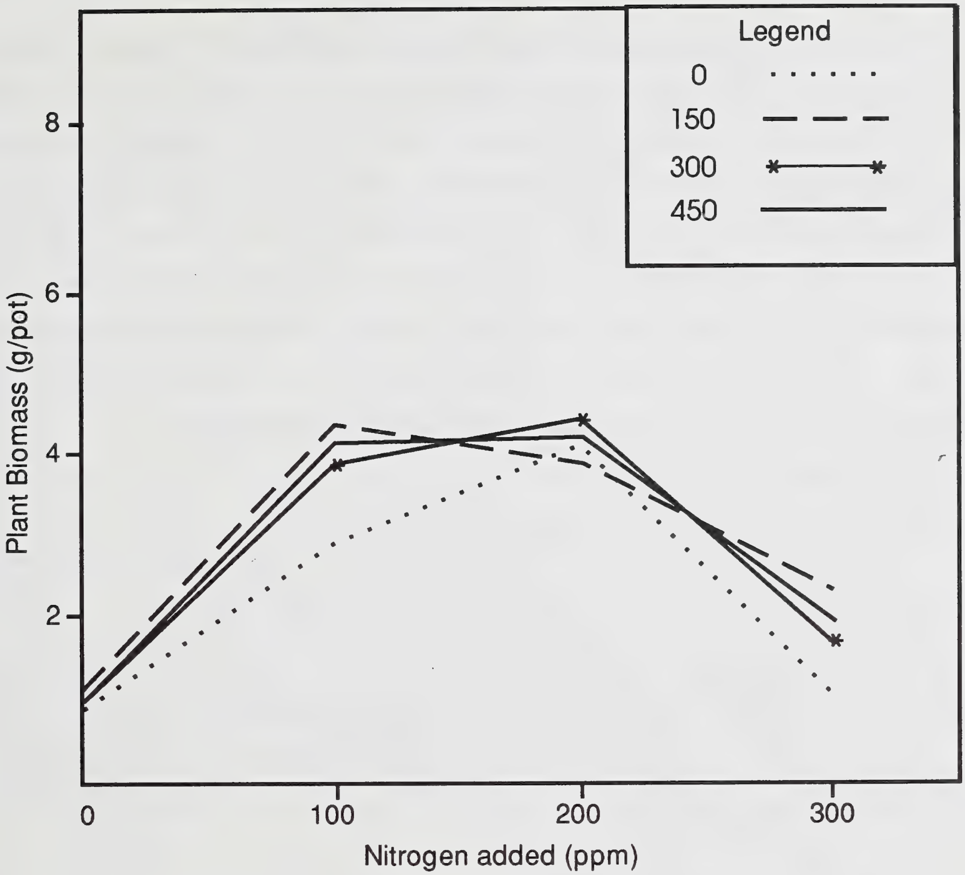


Figure 45. Interaction N x K: The effect of adding nitrogen, at four levels of potassium, on the biomass production of reed canary grass growing on oil sands sludge (n = 12).

removed. The release of nutrients in the thaw water may also have a negative impact on the quality of the water stored for reuse in the plant or released to the Athabasca River. Large additions of nitrogen or phosphorus could lead to algal blooms or other undesirable biological events.

Some fertilization of reed canary grass was vital to the establishment and growth of red canary grass on oil sands sludges. Both nitrogen and phosphorus were essential; the necessity of potassium was less clear. However, nitrogen added at 100 ppm

and phosphorus at 30 ppm was almost as effective as higher doses. If nitrogen addition exceeded 200 ppm there was a noticeable decrease in reed canary grass performance. The cost of fertilization to promote biological dewatering on oil sands sludge can be minimized by adhering to the lowest recommended additions. One should remember that this test examined plant growth for only 73 days starting from the seeding date. The growing season in Fort McMurray is approximately 100 days for a forage grass such as reed canary, and recent findings in field studies show the plants can be started faster with "sprigs" or rhizome pieces instead of seed (Section 6.3). Therefore, the optimal fertilizer amounts identified here may need further refining as field tests proceed.

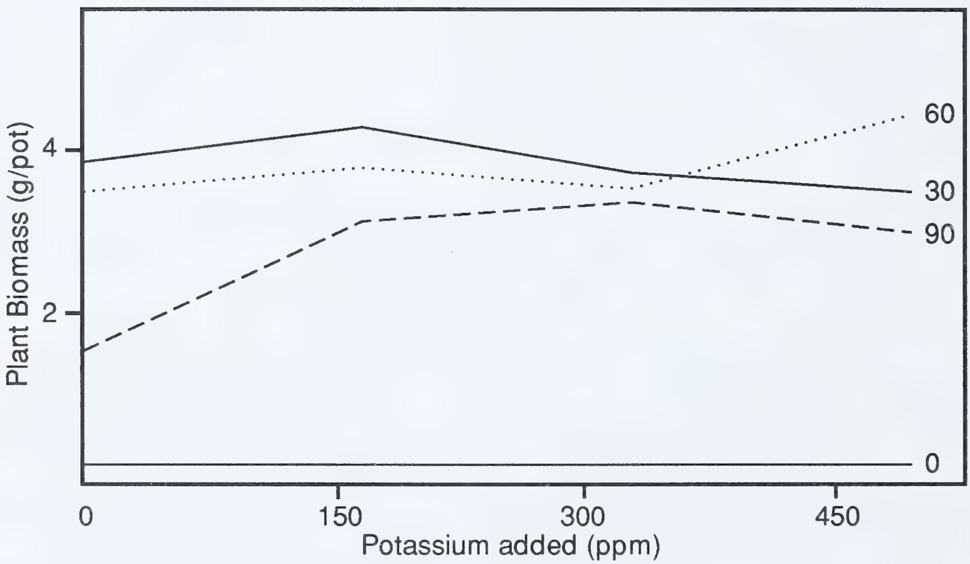


Figure 46. Interaction P x K: The effect of adding potassium, at four levels of phosphorous, on the biomass production of reed canary grass growing on oil sands sludge (n = 12).

6.0 FIELD TESTING FREEZE-THAW AND BIOLOGICAL DEWATERING

The laboratory tests on freezing and thawing described in Section 5 of this report gave consistent results: pure oil sands sludge at 30% solids could be dewatered to approximately 50% solids by one freeze-thaw cycle. The partially dewatered sludge exhibited different characteristics from those of fresh sludge; this was particularly important in devising methods of stabilizing the sludge surface to drain water, preparing the sludge for dewatering by plants and estimating the time needed for complete sludge consolidation.

The laboratory is a special environment, however, and a sludge dewatering technology must be made operational on an enormous scale (25 million cubic metres per year). The next step, therefore, was to test the freeze-thaw and biological dewatering techniques on a field scale.

During the preliminary laboratory tests on freezing and thawing, a load of fresh (30%) oil sands sludge was trucked from Syncrude Canada Ltd.'s Mildred Lake site to the Alberta Environmental Centre. In considering a storage method over the winter of 1986-87 that would not change the characteristics of the sludge, it was decided to build an underground reservoir. The sludge was placed in open pits and allowed to freeze from the surface down. The results of this experiment are described in Section 6.1.

After it was shown that pure sludge undergoing freezing and thawing under field conditions acted like the proven laboratory models, the next step envisioned larger volumes, more elaborate treatments, and actual Fort McMurray climatic conditions. Three crucial additions were made to improve the quality of the data used to justify the new freeze/thaw/biological dewatering technology: sand-sludge mixtures, as well as pure sludges, were tested under ambient freeze-thaw conditions; the possibility of water loss from any other means than surface drainage and evapotranspiration was precluded by using metal bins; and temperature probes were inserted in all treatments to monitor the freezing and thawing fronts and quantify the effect of temperature conductance from the bin sides. It has been shown that freeze-thaw, surface drainage, and evapotranspiration will dewater large volumes of pure oil sands sludge and sand-sludge mixtures to the point

that the surface is stable, and capable of supporting human and vehicle traffic. This experiment is documented in Section 6.2.

Two problems of field management continued to plague the development of dewatering technology: (1) how to provide for surface drainage that is cheap, effective, and operationally feasible on a weak, recently thawed sludge surface; and (2) how to establish plants on the sludge surface immediately after drainage in the spring to successfully dewater at least the upper 50 cm, so that human traffic or overboarding of sludge could occur. Section 6.3 describes a large (50 m^2) field experiment and the development, after several attempts, of a successful method of surface drainage and plant establishment.

6.1 PURE SLUDGE DEWATERING AT THE ALBERTA ENVIRONMENTAL CENTRE: PIT EXPERIMENT

This experiment was established to evaluate the effectiveness of freeze-thaw on oil sands sludge dewatering when larger sludge volumes are left over winter in Alberta. Further, if preliminary dewatering by freeze-thaw was found to be effective under Alberta's climatic conditions, the high solids content product (presumably near 50% solids) needed to be evaluated as a plant growth medium for continued dewatering to a stable, reclaimable surface.

6.1.1 Materials and Methods

In September 1986, about 227,000 L of 30% solids sludge was shipped from Syncrude Canada Ltd. near Fort McMurray to the Alberta Environmental Centre. Two pits (trenches), approximately 7-m long, 1.2-m wide and 1.5-m deep, were excavated in a glacial till soil on the Alberta Environmental Centre site. The sludge was transferred to the two pits in November 1986. Both pits were filled to the top so that the surface of the sludge was even with the surface of the surrounding soil. To monitor the temperature in the sludge during the freeze-thaw cycle, seven thermocouples were installed diagonally across one of the pits (Figure 47) in increments of 25 cm. The five uppermost

thermocouples were Model 101 thermisters and the two lower ones were Model 102 temperature probes. Each type was chosen to suit a specific temperature measurement range. A Campbell model CR21 micrologger (Campbell Scientific, Vancouver) was used to record data from the thermisters and thermocouples.

Temperatures were monitored approximately every 2 weeks from January 1987, to April 1987. Temperatures for November and December 1986, were not recorded owing to an error in calibrating the data logger. The sludge level in relation to the surrounding soil surface was also recorded frequently.

The sludge in one of the pits was sampled in April 1987 at the following locations: at the sludge surface; in the middle; and near the bottom of the pit. One sample per depth was dried at 105°C, and solids content was recorded.

In April 1987, the partially dewatered sludge in both pits was combined to fill one pit back to the original soil surface. The transfer of sludge from one pit to the other was done with a tractor-backhoe.

One half the newly filled pit was transplanted to reed canary grass seedlings placed on 10-cm centres. The seedlings were grown in root trainers under controlled conditions and were hardened off by leaving them outside for 7 days before they were transplanted. The other half of the pit was left unvegetated (bare). The two halves were divided by a plywood sheet (1.9-cm thick), extending 10 cm into the pit sides and 10 cm into the soil at the bottom of the pit.

Neutron access tubes, having a 5-cm diameter and used for moisture monitoring, were pushed through the sludge into the bottom of the pit on both the vegetated and unvegetated sides. Moisture measurements were recorded twice weekly.

The decrease in the depth of the sludge in both sides of the pit was recorded weekly. In September 1987, sludge in both sides of the pit was sampled for strength using a vane shear apparatus (kPa) and mechanical impedance using a cone penetrometer (bars). Solids contents were measured on samples removed at 15-cm intervals. Plant biomass production was measured by weighing a dried (80°C) plant sample clipped from a 0.5-m^2 surface area.

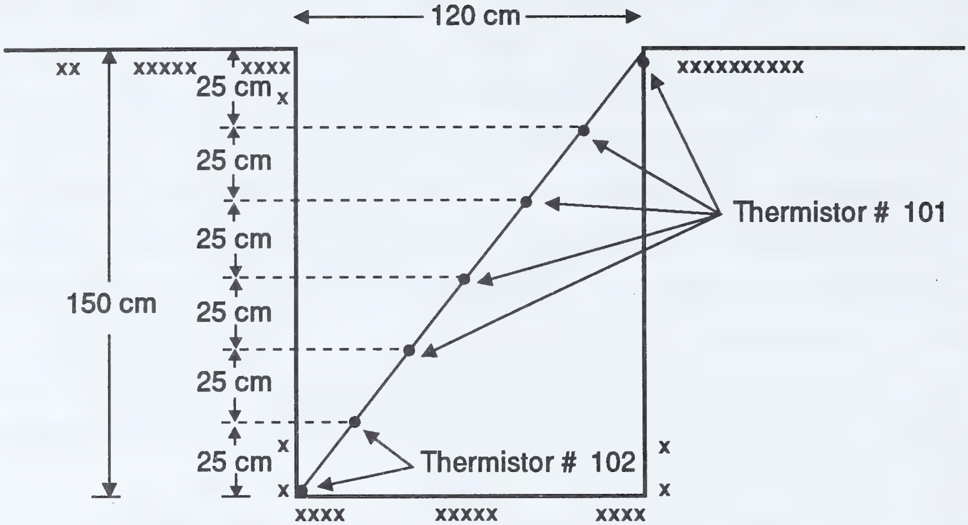


Figure 47. Cross-section view of sludge pit instrumented with thermocouples at the Alberta Environmental Centre.

6.1.2 Results

The pure oil sands sludge froze to a depth slightly less than 100-cm (Table 36) in what could be considered a warmer-than-usual Alberta winter (Table 37). It is important to note that the coldest temperatures of the winter were in November 1986, and sludge temperatures were not being recorded owing to a mechanical failure. It is probable, however, that the sludge did freeze to a 100-cm depth. By April 1 1987, the entire sludge profile was thawed and free water was accumulating on the surface.

In October 1986, the sludge was poured into the trenches at a solids content of 30% (wet weight basis). By April 1987, the upper 15 cm of sludge (underneath a thin surface water layer) had a solids content of 47% and the bottommost sludge (within 10 cm of the trench bottom) had a solids content of 57%. The dewatering that occurred probably resulted from the effects of freezing and thawing and the loss of

Table 36. Temperature (°C) of pure oil sands sludge (30% solids) at various depths in a pit at Vegreville, Alberta from January to April 1987.

Sample depth (cm)	Dates of temperature readings			
	Jan. 8	Feb. 12	Mar. 17	April 9
	(°C)			
0	-3.4	-7.8	-2.5	+7.0
25	-1.9	-5.3	-2.2	+6.2
50	-0.7	-3.2	-1.6	+4.2
75	-0.3	-2.8	-0.3	+0.4
100	+0.9	+0.4	+0.2	+0.2
125	+2.5	+1.7	+1.4	+1.3
150	+2.7	+1.9	+1.5	+1.7

water into the surrounding soil. These effects could not be separated because the pits were unlined. Daily visual inspection of the pits showed that the free surface water at least, if not the water bound within the sludge itself, seeped into the soil.

After the surface water had disappeared from each of the pits, evaporation caused rapid formation of a surface crust. This crust was approximately 3-cm deep before the sludge in the two pits was consolidated into one.

The reed canary grass seedlings were transplanted in early May 1987 onto one half of the pit. On May 15, a late, heavy snowfall covered the transplants and retarded their growth for a short time. However, by September 1987, the reed canary grass had established a complete canopy (Figure 48) and biomass production was 156 g/m^2 (0.7 ton/acre).

Evapotranspiration from a canopy of reed canary grass and evaporation from a bare surface were both effective in dewatering the previously frozen and thawed sludge (Figure 49). The freeze-thaw sludge had an average solids content of approximately 52% when it was combined into one pit in April 1987. By October 1987,

Table 37. A comparison of temperatures, precipitation and evaporation in 1986-87 to a long-term average[1] in Vegreville, Alberta[2].

Month	Temperatures						Precipitation (mm)		Evaporation (mm)	
	Mean max (°C)		Mean min (°C)		Mean temp (°C)					
	1986/87	Long term av.	1986/87	Long term av.	1986/87	Long term av.	1986/87	Long term av.	1986/87	Long term av.
October	12.8	10.9	-0.8	-2.4	6.0	4.0	13.2	16.7	-	-
November	-4.8	-2.0	-15.0	-12.3	-9.9	-7.3	20.9	14.3	-	-
December	-2.2	-9.1	-14.2	-20.2	-8.2	-15.0	9.2	18.0	-	-
January	-3.4	-11.4	-14.8	-22.8	-9.1	-17.6	7.6	15.2	-	-
February	-2.3	-7.4	-12.4	-19.4	-7.4	-13.7	16.0	13.0	-	-
March	-2.2	-1.7	-11.0	-13.4	-6.6	-7.8	19.9	12.5	-	-
April	13.4	9.7	-0.8	-2.9	6.3	3.2	21.6	15.8	-	-
May	19.2	17.9	3.5	2.9	11.4	10.3	35.6	38.2	158	121
June	23.8	21.8	9.5	7.4	16.6	14.5	28.9	70.2	208	120
July	23.6	23.9	9.7	9.8	16.7	16.5	66.6	80.8	154	89
August	18.9	22.9	6.7	8.3	12.7	15.3	68.5	59.9	105.2	98.1
September	20.6	16.6	4.8	3.2	12.7	9.7	64.2	44.4	96.3	51.4

[1] Long-term averages of temperatures and precipitation are based on 29 years for October-December and 30 years for January-September. The long-term average for precipitation is based on 15 years.

[2] All data were provided by the Soils and Crops Substation, Agriculture Canada, Vegreville.

the action of evapotranspiration on the vegetated side and evaporation on the unvegetated side had increased the average solids content, in at least the uppermost 35 cm, to 78% and 72%, respectively. At the surface, the reed canary grass treatment had 88% solids and the unvegetated treatment had 85% solids. Although of the effect of dewatering the pure sludge over the summer and fall of 1987 might have been partly caused by matric suction by the surrounding soil (the test pit was unlined), this component could not be

Figure 48. Reed canary grass growing on pure oil sands sludge in Vegreville, Alberta (September 1987).

separated from the effect of evapotranspiration. The reed canary grass appears to have been slightly more effective at dewatering pure sludge than evaporation alone (Figure 49). This was most apparent at the 15 cm and 25-cm depths.

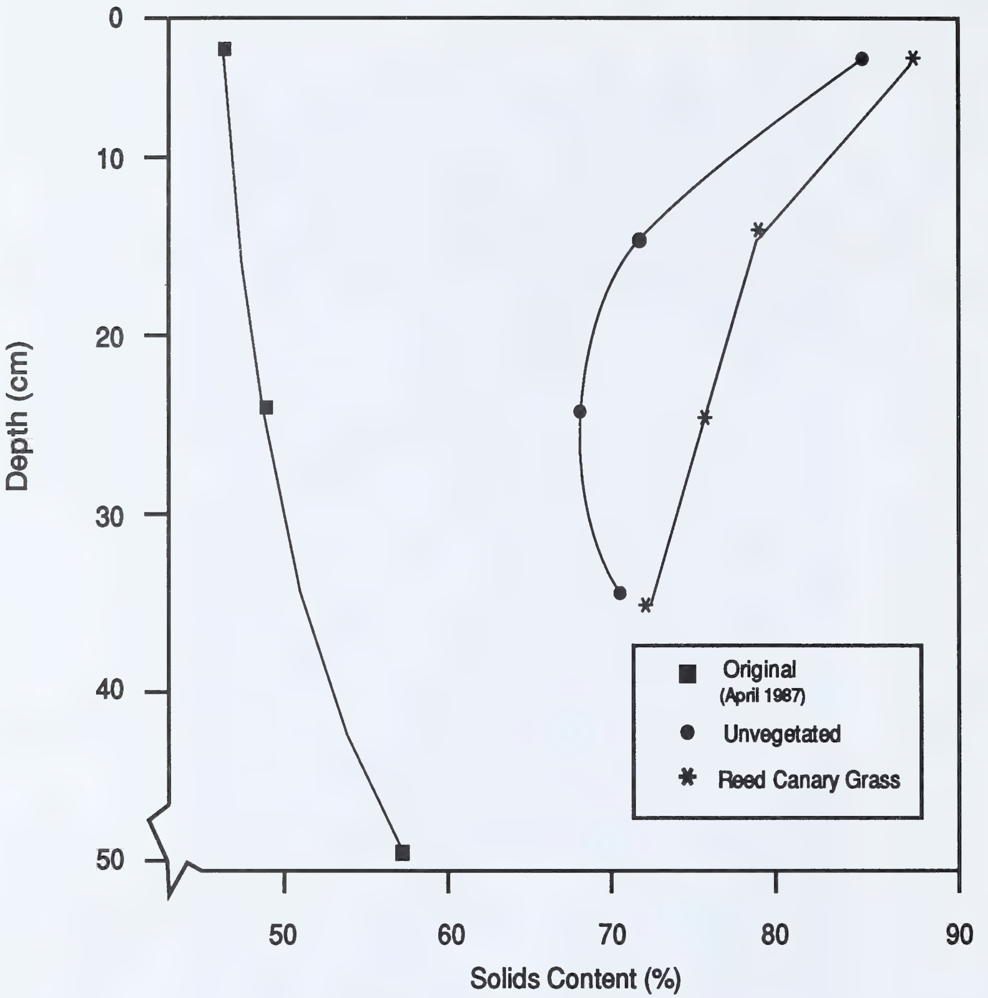


Figure 49. Change in solids content (%) of pure sludge in a field experiment using vegetation and fallow treatments to dewater after freezing and thawing n = 1, original; n = 5, reed canary grass and unvegetated.

The loss of water from sludge increased shear strength. In September 1987, both vegetated and unvegetated sludge had dry 10-cm layers overlying wet sludge at the bottom that was unstable and easily penetrated by a cone penetrometer. The shear strength, using a vane shear, of the bottom layer averaged about 4 kPa; the mechanical

impedance as measured by a cone penetrometer varied from 3 to 9 bars (Tables 38 and 39). The reed canary grass treatment resulted in slightly higher shear strengths at 10 cm than did the unvegetated plot (Table 38). The same conclusion is supported by comparing the two treatment effects as measured by a cone penetrometer (Table 39). By September 1987, the vegetated and unvegetated sludge surfaces could easily bear the pressure of human traffic without movement of any kind (Figure 50 and 51).

6.1.3 Discussion

Although the effects of freezing and thawing on solids concentration in oil sands sludge had been well documented under laboratory conditions (Sections 5.1 to 5.4), field trials had not been done. It has been documented that solids content in sewage sludge is increased by freezing and thawing under field conditions, especially when the freezing action converts the sludge to an easily drained granular material (Rush and Stickney 1979). However, freezing and thawing also concentrated the solids in sludges with a high alum content where drainage by gravity, even after thawing, was minimal (Farrell et al. 1970).

This study provided field evidence for the effect of freezing and thawing on solids concentration in oil sands sludge. Using static freezing (sludge was pumped into a pit at the beginning of winter and left undisturbed until spring), oil sands sludge froze to 100 cm during a mild winter in central Alberta. By shifting the process to Fort McMurray, nearly 500 km north, one might expect the freezing front to be much deeper. Also, more normal winter temperatures would deepen the freezing front.

This field trial, consisting of freezing and thawing followed by a transplant of reed canary grass, provided the first evidence that pure oil sands sludge, like sand-sludge mixtures, was not phytotoxic. In fact, after recovering from the effects of a very late snowfall and an abnormal week of freezing temperatures in spring, the reed canary grass grew well. The biomass production (156 g/m^2) was limited by both a late start and a wide spacing of plants (10 cm apart). Under more favorable agricultural

Table 38. Vane shear strength (kPa) at various depths of partially dewatered pure sludge after one freeze-thaw cycle and one growing season.

Depth (cm)	Treatment	
	Unvegetated	Reed canary grass
	(bars)	
0	61	72
10	12	17[1]
20	4	8
30	2	5
40	4	4
50	5	3

[1] Significantly different means at 0.05 probability level using an unpaired student's "t" test and three random measurements on each treatment.

Table 39. Cone penetrometer strengths (bars) at various depths (n = 3) of partially dewatered pure sludge after one freeze-thaw cycle and one growing season.

Depth (cm)	Treatment	
	Unvegetated	Reed canary grass
	(bars)	
1.0	39	49
3.5	36	50
7.0	19	28
10.5	9	15
14.0	7	9
21.0	5	5
28.0	4	6
35.0	6	5
42.0	9	3

Figure 50. Pure oil sands sludge dewatered over one growing season by reed canary grass.

Figure 51. Pure oil sands sludge dewatered over one growing season by evaporation.

conditions, a reed canary grass stand might produce 210 g/m^2 or 1 ton/acre (Goplen et al. 1963).

Because the pure sludge was dewatered during the summer, it formed a stable surface crust capable of supporting human traffic. Since the crust extended only to 30 cm, it is also apparent that sludge dewatering does not have to extend to a competent layer in order to support traffic. This may have important implications for planning large scale sludge disposal schemes where a surface capable of supporting traffic is the major objective. The results of the field study must be qualified by recognizing that the matric suction of the surrounding soil may have contributed significantly to the dewatering rate, and the size of the pit (1.2 m x 7 m) could have influenced the assessment of surface stability. However, shear strength and cone penetrometer tests on the surface were not related in any way to the surrounding pit sides.

6.2 DEWATERING AT MILDRED LAKE: BIN EXPERIMENT

The use of reed canary grass and western dock plants to dewater both sand-sludge mixtures and pure sludge on a field scale were evaluated in the summer 1987. This experiment was then extended over the winter months (1987-88) to see the effect of freezing and thawing on solids content and volume reduction. The objectives were to evaluate:

1. the ability of plants to establish, grow, and dewater both pure sludge and sand-sludge mixtures; and
2. the dewatering capabilities of freeze-thaw on both the pure sludge and the sand-sludge mixtures.

6.2.1 Materials and Methods

A field dewatering trial was initiated in April 1987, using grain bins as experimental units. Twelve bins were erected on Syncrude Canada Ltd's site at Mildred Lake in April and early May, filled in late May, and given a vegetation (or fallow) treatment in early June.

The bins were 1.83-m high and 4.27-m in diameter with a capacity of 25 m^3. The bin material was galvanized, 20 gauge, corrugated curved sheets of 0.09-cm wall thickness. To form the complete bin, four rings were assembled on top of each other with 3.8-cm overlap; the lowest ring was 0.84-m high and the top three rings were 0.42-m high. This assembly enabled each of the top three rings to be removed when the sludge or the sand-sludge mixture consolidated and dropped in elevation, thereby providing better exposure of the plants to air and light.

The sheets were bolted together using 0.64-cm diameter bolts to form the circular shape of the bin. The spacings between the bolts were 6.4-cm vertically and 25-cm horizontally for all the rings. According to an evaluation of bin stress, it was necessary to install extra bolts vertically on the seams in the lowest ring, at 3.2-cm apart, to overcome the hoop stress on the bin of the sand-sludge mixture or the pure sludge.

Figure 52 depicts the layout of the 12 bins. The 6 bins on the left were filled with sand-sludge mixture and were assembled close to the sand piles (in the background). The 6 bins on the right were filled with sludge and were assembled close to the sludge-storage pit. The bins were assembled about 6-m apart with a large gap in the middle separating the two 6 bin sets. This allowed a weather station to be mounted in the middle to monitor the atmospheric conditions during the experiment.

The bins were assembled on levelled ground. After assembling the bottom ring, soil was placed inside and outside the bin around its walls. The soil was then spread around the bin wall using shovels and was compacted using a jumping jack. Leakage and washout from underneath the bin wall occurred in some of the pure sludge bins owing to poor compaction (Figure 53). Therefore, more soil, a plastic liner, and further compaction inside and outside the bin were required to make these secure and stable.

To prevent leakage from the seams, caulking was applied horizontally and vertically between the bin sheets before bolting them together. Better sealing was achieved by coating the inside of the seams with tar.

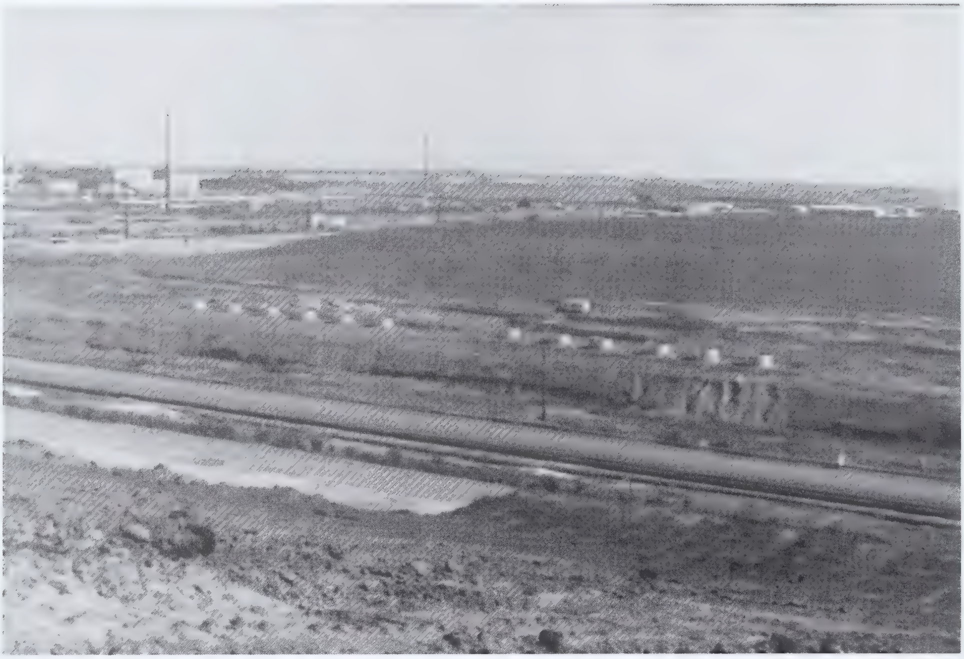


Figure 52. Layout of sludge and sand-sludge bins.

A surface-drainage system was installed in each bin. It consisted of a 3.81-cm vertical pipe sliding inside a 5.08-cm pipe (Figure 54). The outside diameter of the smaller pipe closely matched the inside diameter of the larger one. As the sludge or the sand-sludge mixture consolidated, the uppermost pipe was pushed into the lower pipe, so that the top would be flush with or lower than the surface material in the bin to allow for surface water drainage. The bottom of the lower pipe was hooked to a 90° elbow to drain out of the bin and was supported on firm ground by rocks and stones.

Figure 55 shows the mixing system for the sand and sludge. It consisted of five pieces of equipment:

- cement mixing truck;
- conveyor belt;
- bobcat;
- water pump; and
- two sludge pumps.

Figure 53. Leakage of sludge from underneath the bin wall owing to poor soil compaction.

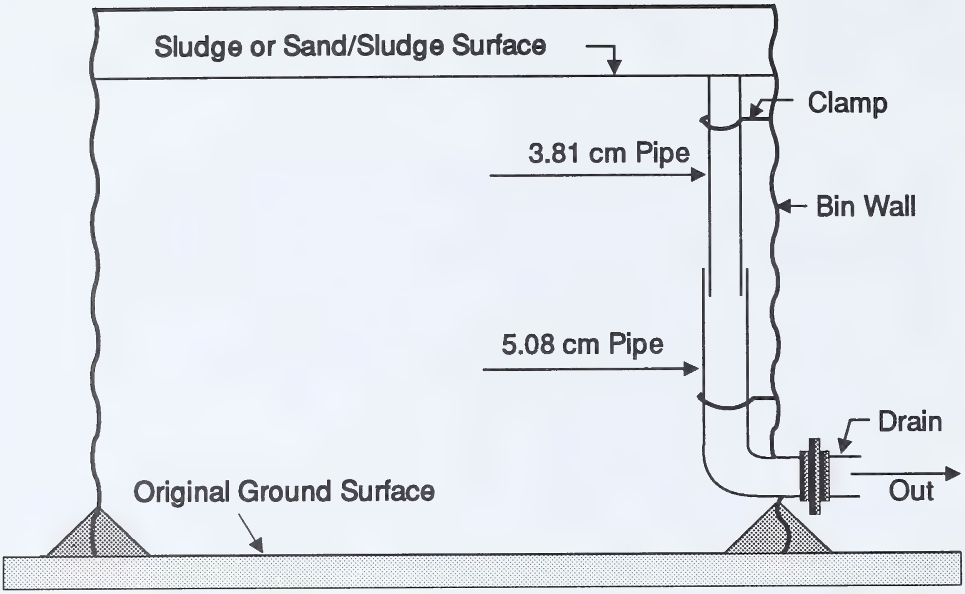


Figure 54. Diagrammatic representation of the drainage system in each bin.

Based on the moisture content of the sand and the solids content of the sludge, tables were prepared to indicate the proportions of sand, sludge, and water required for obtaining a mixture of 50% to 55% solids. A 3:1 sand-sludge ratio was used for all mixtures.

To obtain a homogenous sand-sludge mixture, the cement truck mixing tank rotated while loading the required amount of sand, sludge, water, lime (1,000 ppm dry solids basis) and fertilizer (120 ppm N; 75 ppm P; 75 ppm K; dry solids basis). The sludge and water were measured and pumped directly into the cement truck. The bobcat was used to measure and load the required quantity of sand on the conveyor belt. The conveyor belt loaded the sand into the cement truck. After loading the material, the cement truck continued to mix the contents for 5 to 10 min before unloading the mixture into the sand-sludge bins. A Marcy scale was used to insure that the sand-sludge mixture was within the range of 50 to 55% solids (Figure 56). All six bins were filled in 1 day to insure uniform conditions.

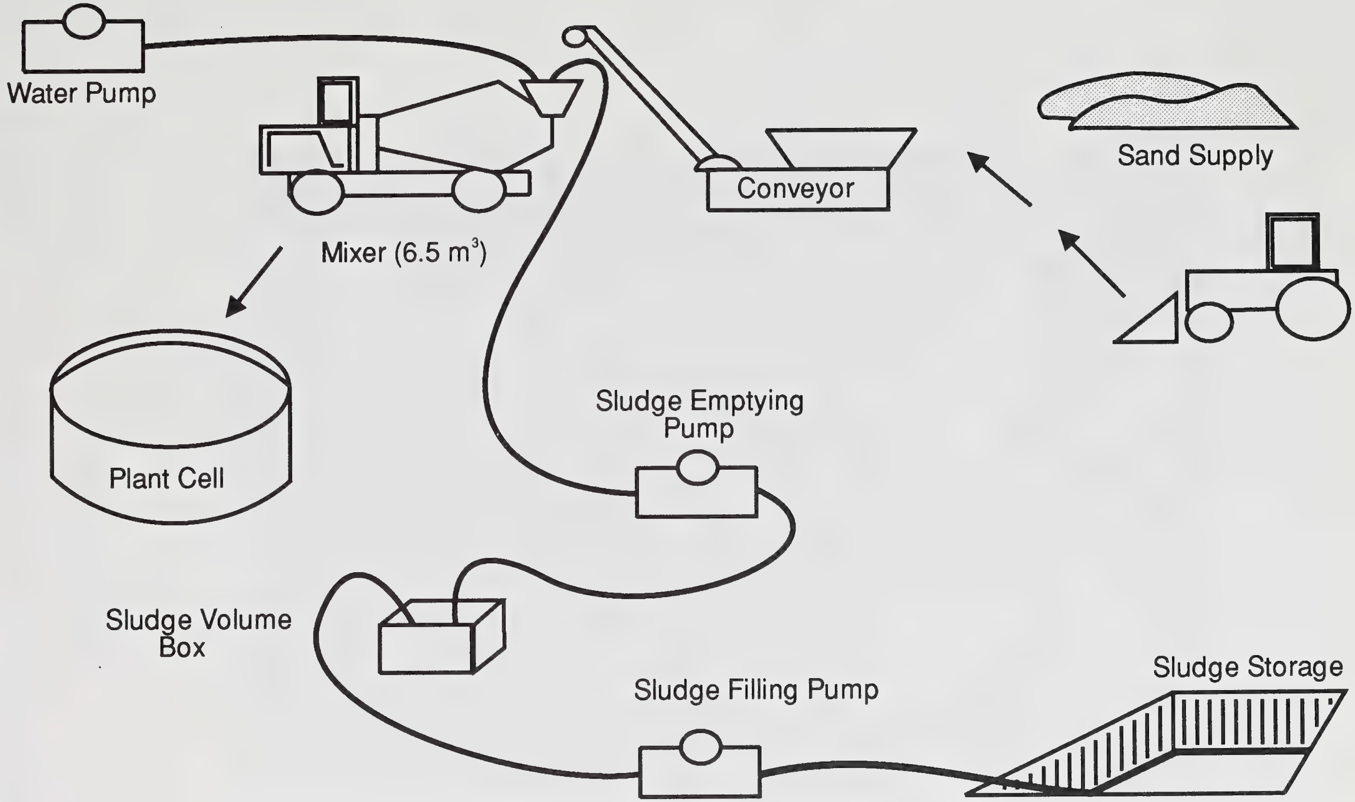


Figure 55. Mixing system for filling the bins. (The sludge bins were filled directly from the sludge volume box by the sludge emptying pump.)

Figure 56. The Marcy scale for determining percent solids of sludge or sand-sludge mixture.

The pure sludge bins were directly filled from the sludge storage pit using diaphragm pumps. While pumping the sludge, the same fertilizer concentration used in the sand-sludge mixtures was added to the bin to ensure proper mixing (Figure 57). The Marcy scale was also used to check that the sludge contained approximately 30% solids.

Each set of six bins, filled with sludge or a sand-sludge mixture was transplanted to reed canary grass, western dock, or left fallow as a control. The three treatments (reed canary grass, western dock, or fallow) were applied to two replicates within each set of six bins. The bins were chosen randomly. The first transplant of reed canary grass and western dock took place on June 15, 1987. The plants were grown in root trainers to the six leaf stage in growth chambers at the Alberta Environmental Centre and hardened off by being left outside the building for 4 days before they were shipped to Mildred Lake for transplanting.

The plants were pushed into the sludge or sand-sludge mixture on 20-cm centres (Figure 58).

A second transplant was made on July 10, 1987 to fill in large surface areas where the original plants did not survive. These seedlings were obtained in the same manner as the first lot.

On August 1, 1987 four pure sludge bins were skimmed mechanically to remove the surface crust (created through surface evaporation) and seeded to either western dock or reed canary grass (two each). The two pure-sludge bins which were not reseeded by mulching in 1987 were one of the fallow bins (no vegetation from the beginning) and one bin containing several dozen healthy western dock plants. A 1-cm layer of dry peat was spread evenly across the surface, and seed was broadcast on top (20 kg/ha reed canary grass, 13 kg/ha western dock). Finally, a covering layer of peat (1 cm) was spread over the seeds (Figure 59) and wetted down periodically (every 2 to 3 days).

In July 1988, when it was obvious that the plants grown from the mulching experiment of 1987 had not survived the winter, these four bins were skimmed off again and reseeded using a cellulose-based mulch.

Figure 57. Fertilizer added while filling bins with sludge.

Figure 58. Reed canary grass transplants.

Figure 59. Spreading mulch and seeds on top of sludge.

In November 1987, all 12 bins were instrumented with type T thermocouples located at three depths: top, middle, and bottom. Each thermocouple was fabricated by amalgamating the copper and constantan wires at one end of a thermocouple strand with subsequent corrosion protection provided by a silicon seal. The opposite end of the strand was fitted with a monitoring plug. Supports for the thermocouples were constructed of metal stakes to which 8-cm wide insulating plywood strips were attached. The thermocouples were stapled to the plywood at two, 120-cm increments from and including the bottom, placing the top thermocouple within 20 cm of the surface. The finished sensing units were driven through the sludge layer in each bin and into the earth base to a depth of approximately 45 cm. With the exception of one bin filled with sand-sludge mixture (bin 3) and one bin filled with pure sludge (bin 9), the thermocouple units were installed vertically near the centre of each bin. The other two bins were instrumented with 12 thermocouples, three each on four stakes placed vertically in a diametric line through the sludge (Figure 60). All thermocouple leads ran from the bins to holding boxes to protect the monitoring plugs from the elements.

Temperature readings for each thermocouple were taken at an average of 6 day intervals during the period November 26, 1987 through June 7, 1988. Measurements were made using a hand-held thermocouple thermometer Model #8528-20 from Digi-Sense.

The sand-sludge mixtures and pure sludge were sampled and tested at random locations within the bin. With the exception of biomass measurements, all samples and tests were replicated at least twice. Samples for solids content were collected at 30-cm intervals with a sludge pit sampler fabricated at the Alberta Environmental Centre. Each sample was oven dried at 105°C for 24 h; solids content was determined on a dry weight basis. Crust thickness was determined by removing a section of the sludge surface, allowing the liquid portion of the sludge to drain, and then measuring the thickness of the solid material. Crust strength was measured using a

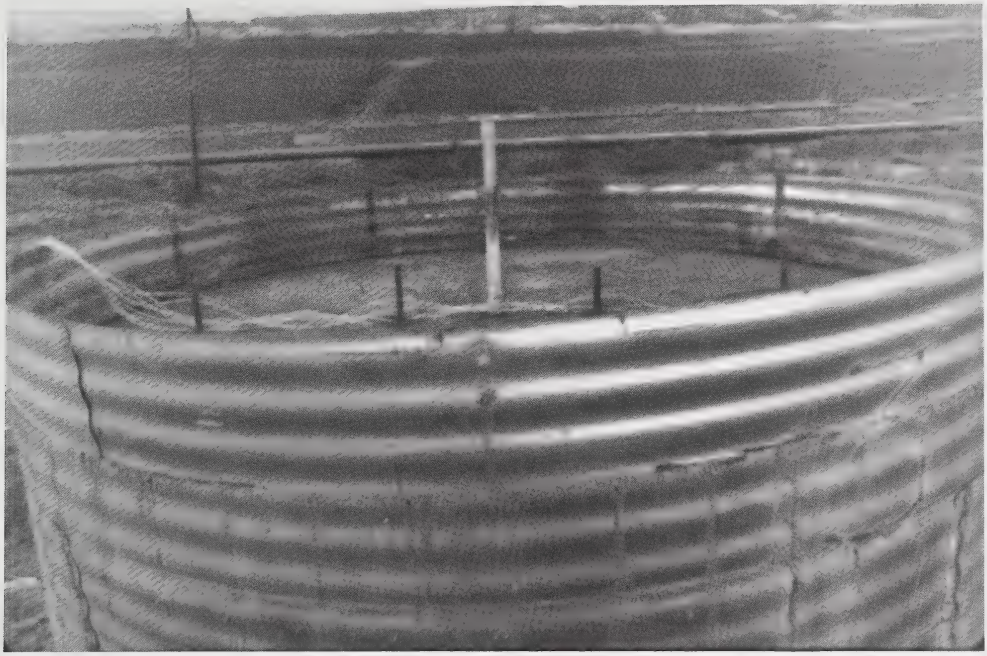


Figure 60. Location of sensing units in bins 3 and 9.

Pilicon model #19-01-00 vane shear. Biomass determinations involved harvesting a 1-m^2 area in each bin. The material collected was oven dried at 70°C for 24 h and then weighed.

6.2.2 Results

The first transplant of both reed canary grass and western dock on sand-sludge mixtures and sludge alone was not successful (Figure 61). Less than half the plants survived on the sand-sludge mixture and almost all the plants died on the 30% solids pure sludge.

One replicate of the 30% solids sludge treatment transplanted to western dock (bin # 12) prospered enough to be left alone after the first transplant. After approximately 30 days, this replicate had about a 60% cover.

A second transplant on sand-sludge mixtures in the last week of June 1987, was more successful. From 60% to 75% of both plant species survived on the sand-sludge mixtures. The second transplant of reed canary grass and western dock (1 replicate only) on the sludge treatment was no more successful than the first. Fewer than 10% of the transplants survived.

At the end of July 1987, both replicates of the pure sludge treatment assigned to reed canary grass, one replicate of the western dock, and one control bin were surface skimmed to remove the crust formed as a result of evaporation. Then they were seeded to western dock and reed canary grass. By spreading the seed on a peat mulch and watering until saturated, excellent germination and establishment was achieved, especially for reed canary grass (Figure 62). This plant cover continued to grow until the first heavy frost of late September 1987. By that time, the reed canary grass was 6-cm high and the western dock had developed to the 6-leaf stage.

The biomass production for western dock growing on sand-sludge mixture after 3.5 months was more than 10 times that of reed canary grass. The one replicate of western dock that survived on the 30% solids pure sludge produced approximately the same biomass as that growing on sand-sludge mixtures:

Treatment	Plant species	Biomass (g/m^2)
sand-sludge	reed canary grass	2.2[1]
sand-sludge	western dock	25.7[1]
sludge	western dock	29.6[2]

[1] Average of two replicates
[2] One replicate only

Although the planted bins filled with sand-sludge mixtures did not form a deeper crust during the summer than the unplanted bin (fallow), the strength of the crusts associated with the planted bins was slightly higher (Table 40). The surface crusts

Figure 61. Unsuccessful transplant of reed canary grass.

Figure 62. Successful establishment of reed canary grass from seed.

Table 40. Properties of surface crusts formed on sand-sludge mixtures or sludge after one growing season.

Treatment	Crust Properties		
	Thickness (cm)	Strength (kPa)	Solids (%)
Sand & Sludge Mixture[1]			
Control	4.3	0.3	67.5
Reed canary grass	4.3	1.2	67.7
Western dock	5.0	1.0	69.0
Sludge[2]			
Control	7.0	---	79.8
Western dock	7.5	---	64.2

[1] All data are averages of two replicates
[2] All data are from one replicate only

Table 41. Solids contents of the sand-sludge mixture and pure sludge after one winter of freeze-thaw. (All data are averages of six replicates sampled in July 1988).

Depth (cm)	Solids Content of Material	
	Sand-Sludge	Sludge
	(%)	
Crust	87.7	68.5
30	79.7	52.1
60	80.7	56.9
90	81.0	----[1]

[1] Sludge consolidation eliminated the 90-cm depth measurement.

formed on bins of sludge at 30% solids were somewhat thicker than crusts on sand-sludge mixtures. There was not a significant difference in the solids content of surface crusts formed on either material, nor did plants seem to increase or decrease it.

By September 1987, the sand-sludge mixtures and the sludge had not changed in solids content below the crust layer (data not shown). The average solids content of the sand-sludge mixture upon pouring (June 1987) was 55.2%; for the pure sludge bins, the average was 36%. After one winter of freeze-thaw, however, where outside temperatures reached -35°C and the coldest in-bin temperatures for sand-sludge mixtures and sludge were -20°C and -15°C, respectively, the solids contents of both materials increased dramatically. The sand-sludge increased from 55% solids to 80% solids at all depths to the bottom of the bin (Table 41). At 80% solids, the sand-sludge mixture had sufficient strength to support a 90-kg man walking on the surface (Figure 63).

Also, there was a large increase in solids content due to freeze-thaw in bins containing pure sludge. Starting from 36% solids in September 1987, the average solids content was between 52% and 57% by mid-summer, 1988 (Table 41). This range excluded the very high solids crust (68.5%), formed as a result of surface evaporation.

Dewatering by freeze-thaw also led to considerable material consolidation and volume reduction. The sand-sludge mixtures lost 45% of their original volume (Figure 64). By August 1990, the sludge bins lost 85% (Figure 65). The larger amount of consolidation in pure sludge, compared to that in those as the sand-sludge mixture, was caused by the lower original solids content (36% vs. 55%) and the smaller average pore size.

Temperatures recorded at three depths in the bins followed similar freezing patterns as shown in Figures 66 and 67. These patterns coincide with concurrent ambient temperature data plotted from Environment Canada's Fort McMurray weather station (Figure 68). The coldest temperatures, achieved throughout the bins during the early part of February 1988, are given in Table 42. The data also indicate that the sand-sludge cooled faster and reached lower temperatures than the pure sludge at each depth.

Figure 63. Demonstration of the bearing strength of sand-sludge mixture at 80% solids.

The thermal boundary effects, caused by the exposed, non-insulated metal sides of the bins, are evident in the temperature data relating to the pure sludge bins (Figure 69). In this case, the minimum temperature reached at the bottom sensor closest to the middle of the bin was -3.2°C, in contrast to -15.5°C recorded by a sensor at the same depth placed near the outside wall.

It is obvious that the freezing isotherm progressed from the surface down through the sand-sludge or pure sludge layer (Figures 66 and 67) as well as from the outside in (Figure 69).

The surface drainage system manufactured from pipe did not work. As the sludge surface dropped, the drainage pipe impeded the flow of water off the surface. Holes were drilled in the bin sides to drain off the expressed water.

6.2.3 Discussion

It was not easy to establish plants on either the sand-sludge mixtures or sludge. Transplants appeared to undergo "shock" when they were pushed into sand-sludge mixtures at 55% solids, and many plants died before new root-systems formed. Transplants in 36% solids sludge were unstable and frequently tipped over and perished. Even when they succeeded in remaining upright, the plants in sludge underwent a similar "shock" as those transplanted into sand-sludge. Transplanting reed canary grass or western dock did not appear to be a viable approach to sludge dewatering.

It was relatively easy to establish both plant species on sludge from seed when care was taken to mulch the surface with peat and keep the seeds and mulch moist. Reed canary grass established much faster than western dock under these conditions and reached 6 cm in height before autumn frosts stopped its growth. However, the thick cover of reed canary grass and the thinner, but sufficiently populous, western dock growing on sludge in September 1987 was completely dead by late spring 1988. The winter freezing, the spring thaw and subsequent water accumulation, or the drastic reduction in volume (up to 71%) killed the small plants left to overwinter. Forage crops grown on more southern agricultural soils suffer severe winterkill as well. Seeding in

Figure 64. Volume reduction in a sand-sludge mixture caused by dewatering.

Figure 65. Volume reduction in pure sludge caused by dewatering.

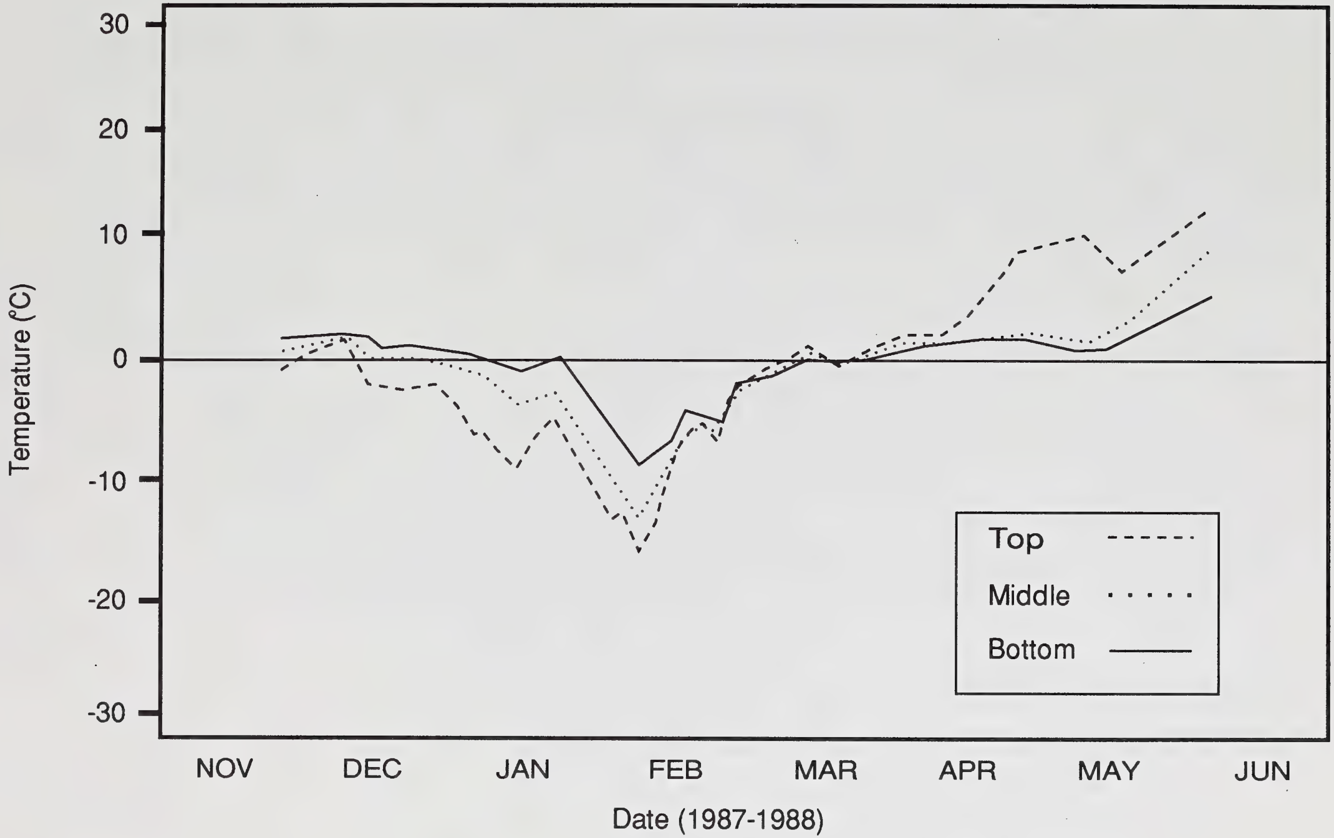


Figure 66. Average in-bin temperatures for three depths within the sand-sludge layers.

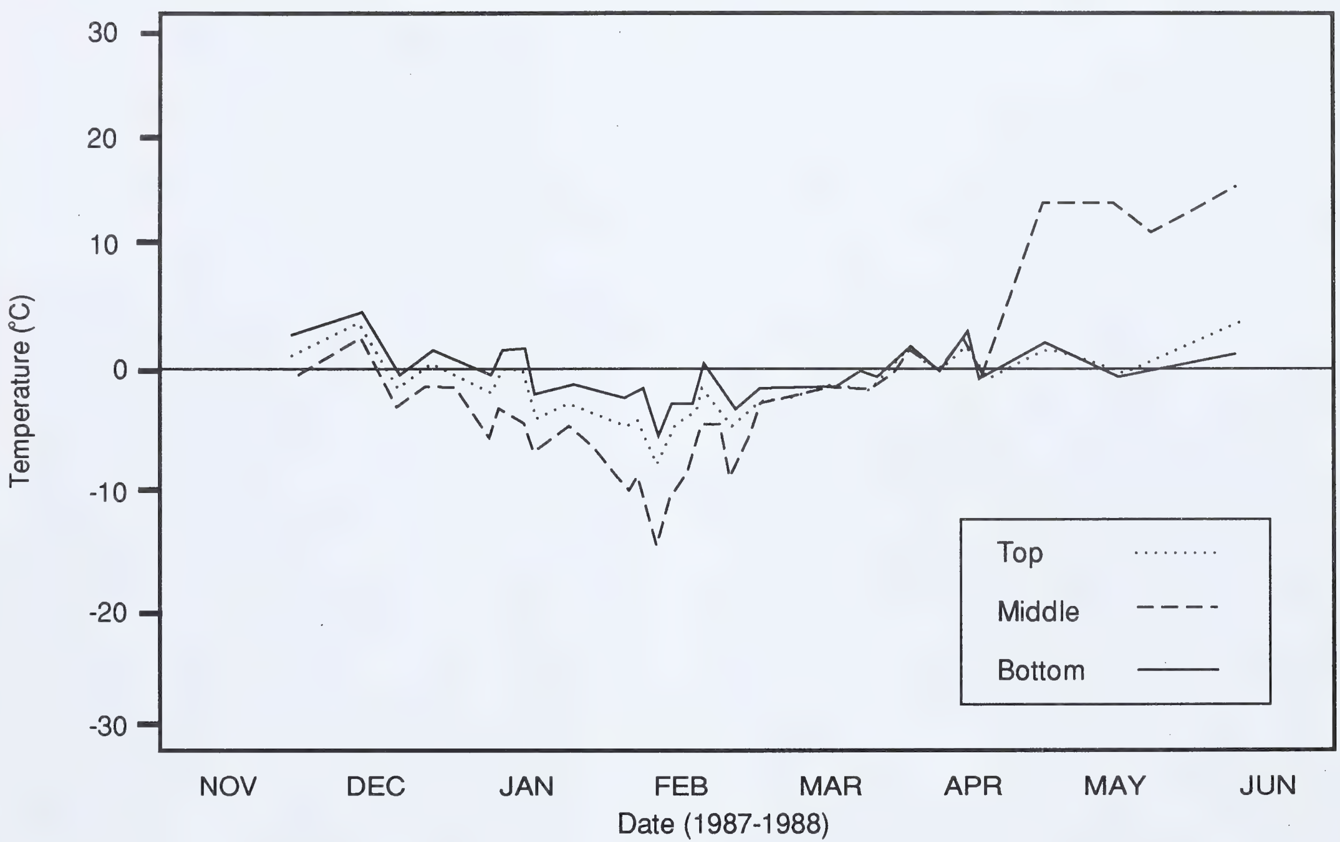


Figure 67. Average in-bin temperatures for three depths within the pure sludge layers.

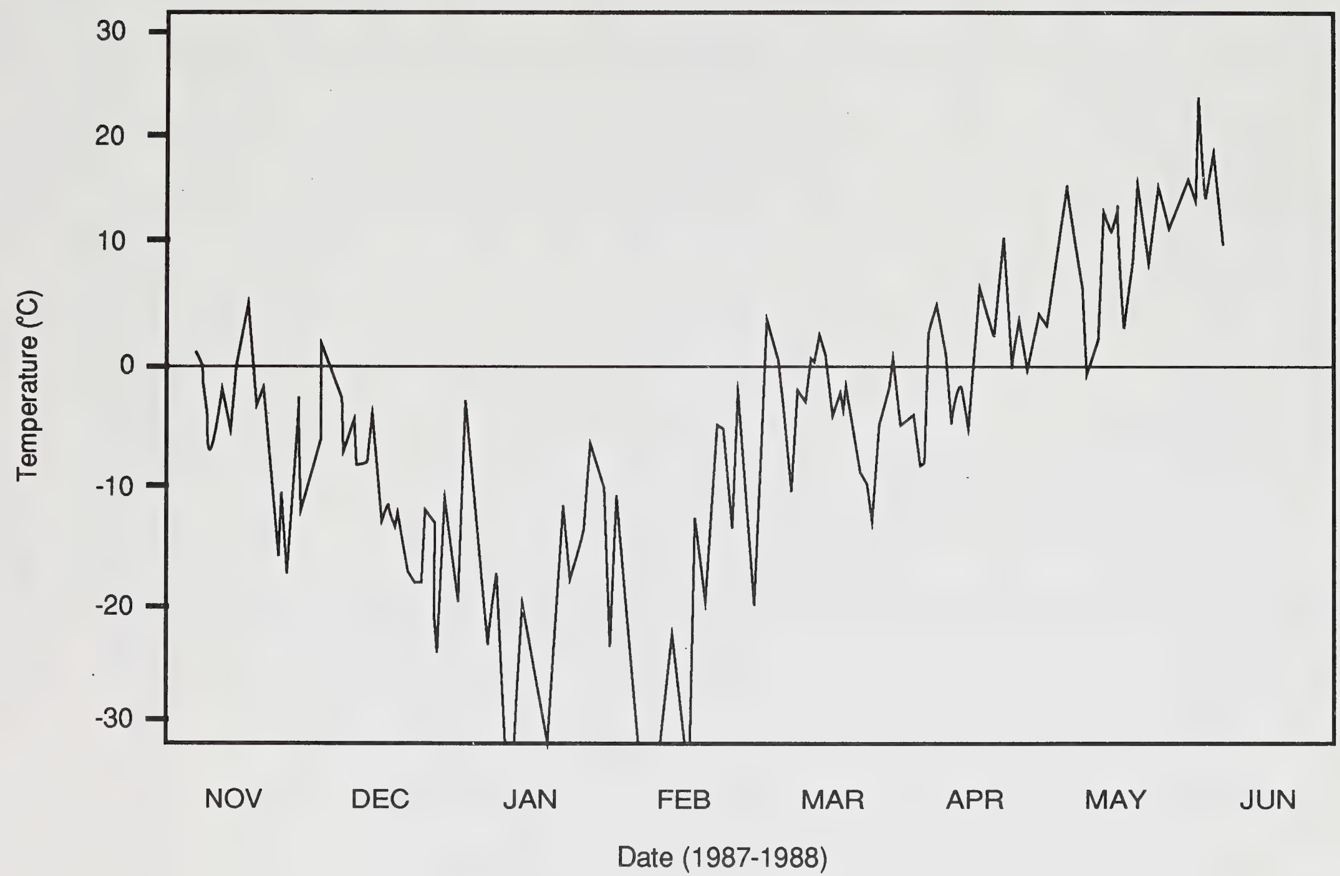


Figure 68. Environment Canada's average ambient daily temperature for Fort McMurray area.

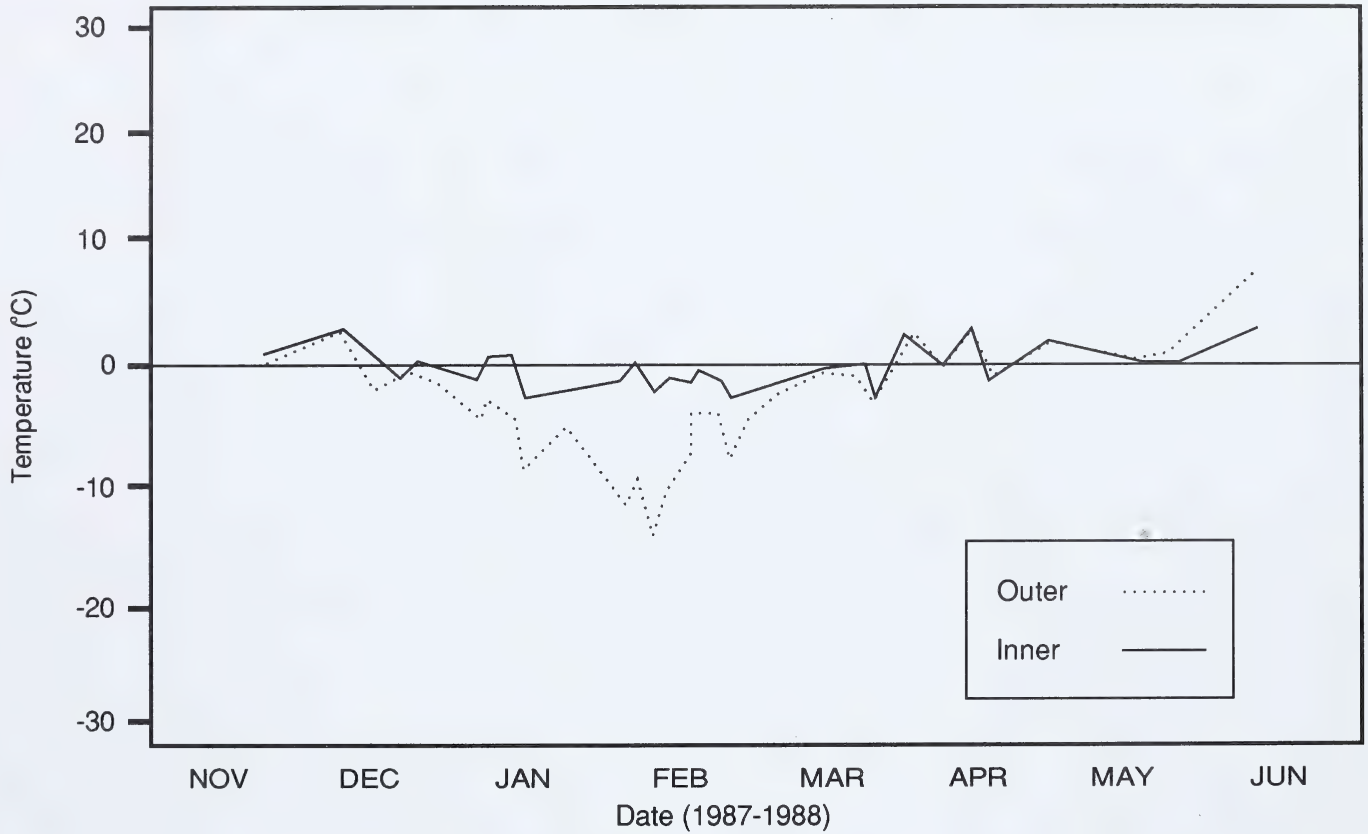


Figure 69. Boundary effect on temperatures within the pure sludge layer (Bin #9).

Table 42. A comparison of the lowest recorded temperature for thermocouples at three depths.

	Thermocouple position	Lowest temperature (°C)
Sand-sludge	Top	-18.2
	Middle	-14.7
	Bottom	-10.0
Pure sludge	Top	-13.9
	Middle	-7.1
	Bottom	-5.5

midsummer, or even early fall, results in a small seedling which does not have the necessary reserves to overwinter. Earlier experiments done at the Alberta Environmental Centre in Vegreville show that sludge-grown reed canary grass will overwinter easily if the plants are larger and more mature.

Although it was difficult to establish and produce plants on either sand-sludge or sludge in the grain bins, there was a large amount of water lost by the purely mechanical forces of freezing and thawing. Both materials lost approximately the same amount of water over one winter (25%), although sand-sludge mixtures started at 55% solids and sludge started at 36% solids. The strength of the sand-sludge mixtures at 80% solids (after one winter of freeze-thaw) was sufficient to support one person. Research has shown that sand-sludge mixtures need to be at 85% solids or higher to support heavy traffic, construction or sludge overboarding (Shaw 1984). In terms of strength, measured by the vane shear, 85% solids in sand-sludge mixtures signifies 100 kPa or more. Therefore, these mixtures have lost almost enough water to ensure complete stability.

Sludge without sand at 55% to 60% solids is not stable. Surface strength is less than 5 kPa. Further dewatering to 80% solids is necessary to increase strengths to more than 100 kPa (Isaac 1986).

The effect of freezing and thawing on dewatering depended on the degree of frost penetration into the material. Since sub-zero temperatures were recorded at all monitoring locations within the bins, it was deduced that both the sand-sludge and the pure sludge were entirely frozen. The difference in freezing rate and the resulting difference in minimum temperatures in the two materials were caused by their variance in thermodynamic properties, mainly the latent heat of freezing. With similar initial volumes, the pure sludge froze slower than the sand-sludge, owing to its higher water content (55% versus 36%).

6.3 DEWATERING AT MILDRED LAKE: PIT EXPERIMENT

The encouraging results of the dewatering experiments conducted at the Alberta Environmental Centre and those in the bins on the Mildred Lake site led to a request to conduct larger field experiments. The major limitations of the pit experiment at the AEC site were: size (the pit was only 7-m long and 1.2-m wide); the confounding influence of the soil on the moisture withdrawal from the sludge (the pit was unlined), the difference in climate between Vegreville and Fort McMurray (or Mildred Lake); and the lack of replication (there was only one pit). The bin experiment increased the size considerably (approximately 25-m^3 sludge/bin) and moved the test to where the sludge ultimately would be dewatered (Mildred Lake). However, the bins had the distinct disadvantage of conducting heat and cold from the sides as well as from the surface, a condition that would not be found under operational conditions in the mined-out pit. The solution, therefore, was to conduct another experiment at Mildred Lake on an even larger scale than afforded by the bins. This time, a pit experiment would ensure that the sludge was frozen and thawed only from the surface down. To avoid the confounding influence of the surrounding soil, the pit would be lined with an impermeable barrier.

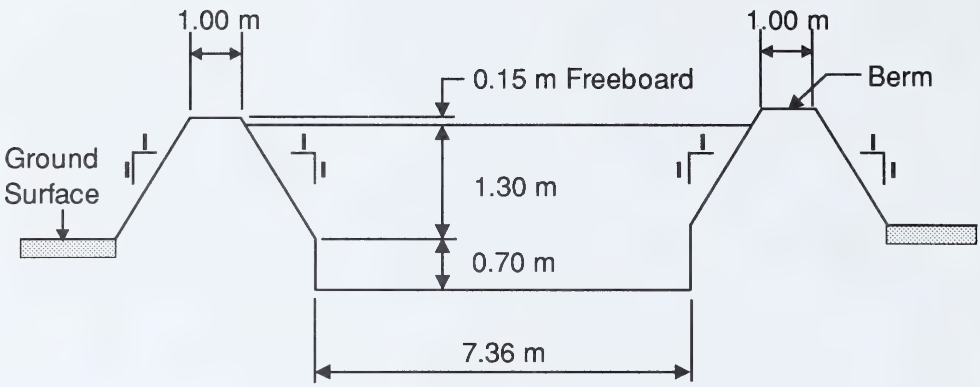
The objectives of the pit experiment at Mildred Lake were: (1) to test the effect of freeze-thaw dewatering on pure sludge on a large scale where temperature differences could only occur from the top down; (2) to evaluate three ways of controlling surface drainage after sludge thawing--sand surcharges on the surface of the frozen sludge, bottom-placed sand mounds to create surface depressions, and a sloped floor on the pit bottom; and (3) to develop a method for rapidly establishing plants on the sludge surface.

6.3.1 Materials and Methods

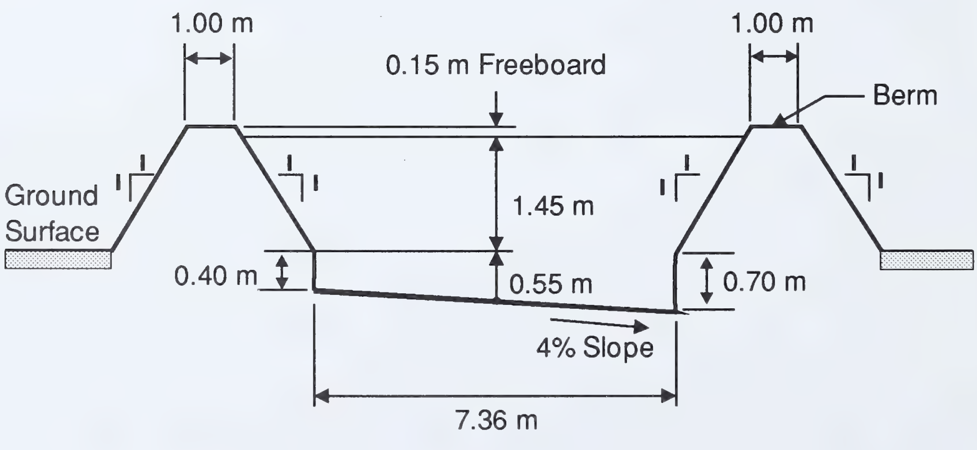
Two large-scale (60 m^2 x 2-m deep) dewatering pits were constructed on Syncrude Canada Ltd's site at Mildred Lake, north of Fort McMurray. The two pits were located south of the bin experiment, where there was good drainage and sufficient room for the excavations, including the dykes. The east pit was built with a level bottom. It had vertical walls of 0.7 m, and 1.45-m high dykes with 1:1 side slopes (Figure 70). The dyke berm was 1-m wide. The west pit was formed with a 4% sloped bottom from east to west and with the same base dimensions as the east pit. The vertical wall on the east side of the west pit was 0.4-m deep, while the vertical wall on the west side was 0.7-m deep. Other dimensions are similar to the east pit (Figure 70).

Syncrude Canada Ltd. provided machines and equipment to build the two pits. A backhoe was used to excavate the base to a depth of 0.7 m. The material excavated from the pits was placed outside the immediate perimeter of the pit to form the dyke. A bulldozer compacted the material of the dyke and gave it the desired side slope of 1:1. Bottom and dyke elevations were monitored until the desired level was attained.

Each pit had all four dyke walls cut by the backhoe to form channels for future sand placement. The depth of the channels was measured to approximate the original ground surface level. A thin layer of sand was placed in the drainage channel for the drain pipe bed. A 6.1-m long PVC pipe, 38 mm in diameter, was placed in each channel, recessed about 0.6 m from the inner dyke face. This was done so the sludge surface water would flow through the sand channels and be drained by these pipes to the



East Pit



West Pit

Figure 70. Cross-section views of east and west pits used to test dewatering by freeze-thaw.

phreatic line. The pipe entrance had screening attached to prevent gravel from moving with the drain water. A gravel filter was placed over the pipe entrance to prevent sand fines from washing into the pipe. The channel was then filled completely with sand and compacted to the same shape as the dykes. Figure 71 shows the location and dimensions of sand mounds running along the floor of each pit. In the west pit they ran parallel to the slope of the bottom. The mounds were 0.5-m high x 0.5-m wide x 7.36-m long. They were and located 1.8 m from both sides of each pit. The purpose of these sand placements was to form humps in the surface of the sludge after it had thawed (See Section 5.7), and thereby assist in draining surface water from the sludge.

To eliminate water seepage to the surrounding dykes or the ground underneath, a liner was installed in each pit. The liner was made from 20 mil woven polyethylene, prepared and cut to 16 m x 16 m. It was placed to line the inner dyke slopes and conform to the bottom contours of the pits. The portions of the liner above the sand channels were cut out and removed to allow surface thaw water and rain to drain through the sand (Figure 72).

Type T thermocouples for both pits were prepared by separating a set of 20 cables from a bundle of wires. Each cable consisted of two wires made of two different metals. The end of the wires in each cable were bound together and covered with silicon to protect against corrosion. The other ends of the thermocouples were attached to male plugs. The thermocouples were tested in the field by measuring the air and water temperature against a thermometer (ASTM 1986).

Ten thermocouples were used in each pit. Six thermocouples were installed diagonally on a holder made of perforated angle iron, and the rest of the thermocouples were assembled vertically on a post in the middle of each pit. The different points, locations, and depths at which the temperature was measured in the two pits are shown in Figures 73 and 74.

The ends of the thermocouples in the pits were extended away from the angle iron to avoid heat transfer from the metal. All the thermocouples from the central

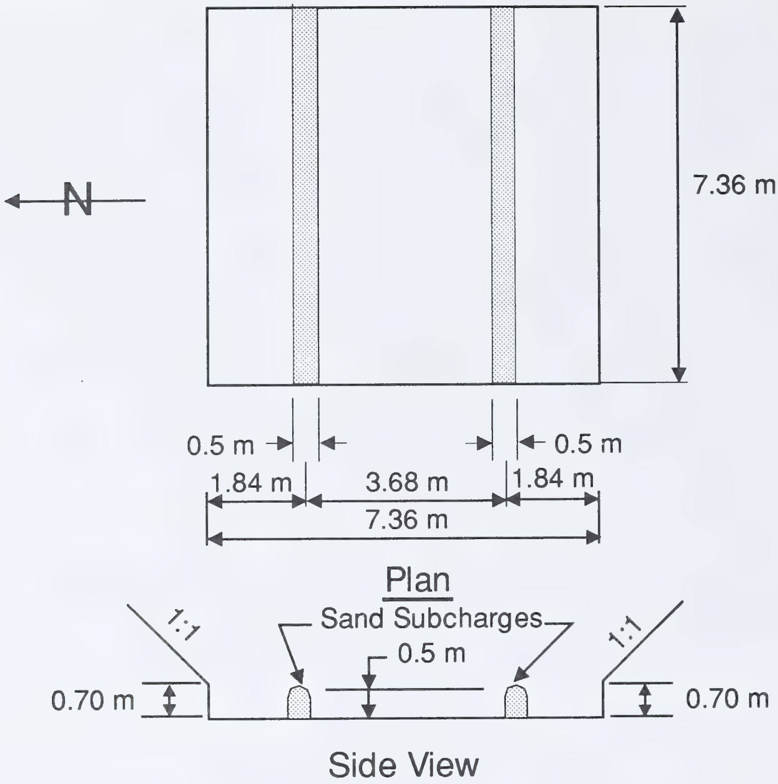


Figure 71. Sand placement on pit bottom: location and dimensions.

post and on the angle iron were tied together and had their electronic plugs stored in wooden boxes for protection from adverse weather conditions.

The temperatures in the two pits were monitored from November 1987 to June 1988, using a thermocouple thermometer (Digi-sense Model No. 8528-20). The ambient operating temperature of this meter was 5°C to 25°C; therefore, it was used from a truck cab during sub-zero temperatures. The thermocouple monitoring plugs were brought to the truck and kept inside with the meter until their temperature was between 5°C to 25°C before plugging the thermocouples into the meter and taking the readings. Ambient air temperatures were also recorded.

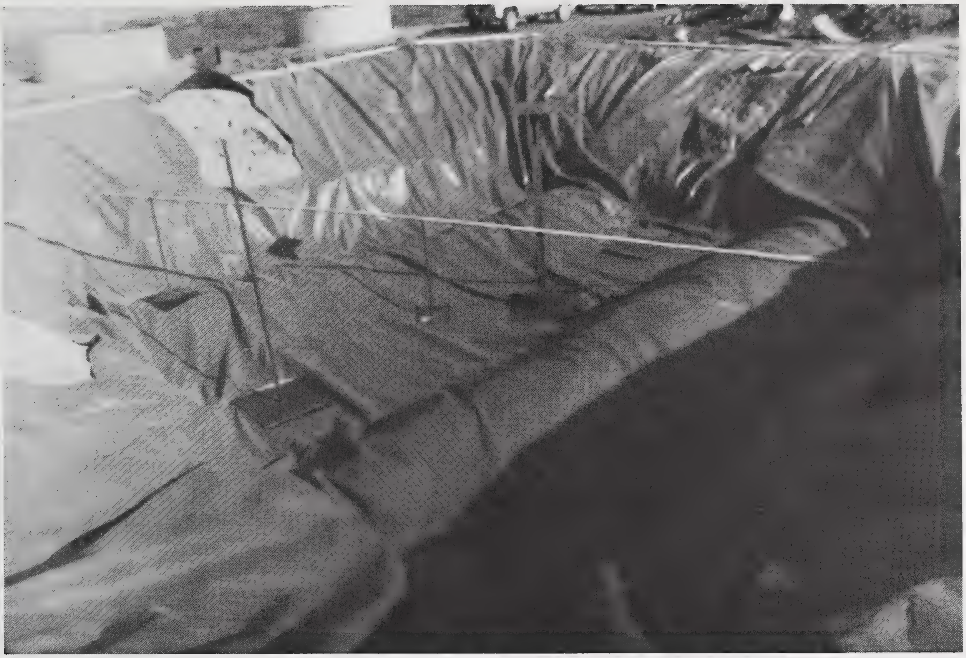


Figure 72. Cutting out the liner at the sand channel interface.

Depth stands were made of vertical angle iron welded onto a 61-cm x 61-cm x 0.9-cm plate. These depth stands were marked every 10 cm and were positioned at different locations in the pit to monitor the sludge elevation in the pits. Rubber fibre mats were placed under the middle post and the stands to prevent liner puncture.

A 7.5-cm diaphragm trash pump was used to fill the two pits with sludge. The bottom channels of both pits were initially filled to hold the liner in place (Figure 75). The filling proceeded by alternating between the east and west pit every 10 to 30 cm depth, thus ensuring similar sludge characteristics in both pits. Samples of sludge were taken during pumping to determine the sludge solids content. Other sludge samples were taken at 10-cm intervals after the two pits were filled with sludge.

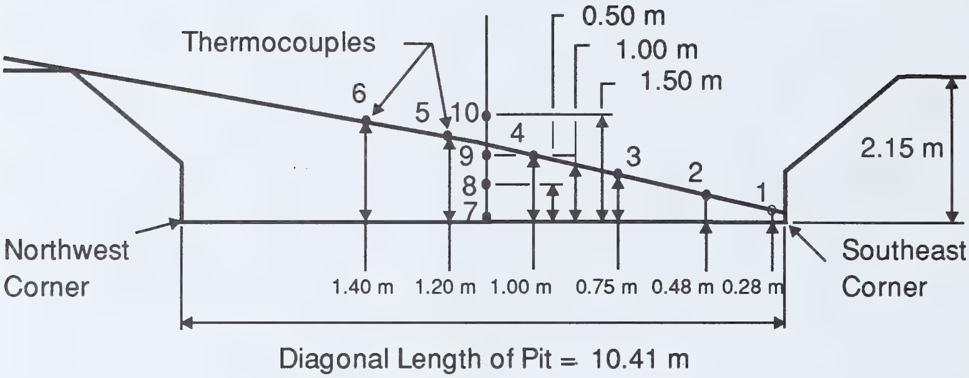


Figure 73. Installation of thermocouples in the east pit (diagonal cross-section).

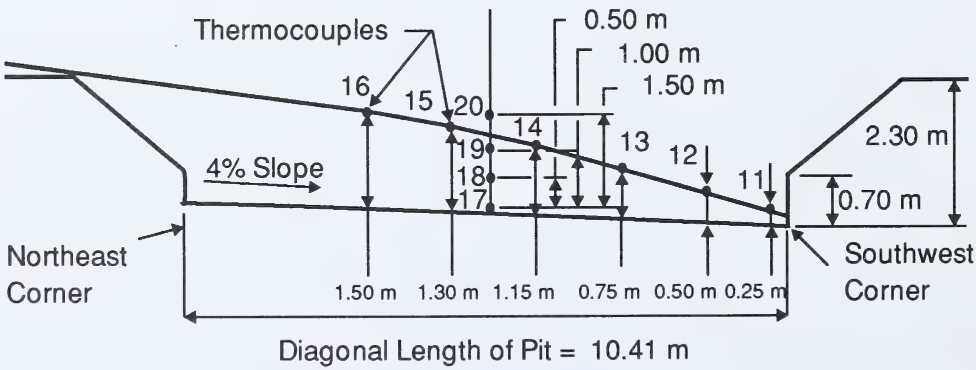


Figure 74. Installation of thermocouples in the west pit (diagonal cross-section).

Figure 75. Filling the pits with sludge.

The two pits were then left to freeze during the winter of 1987-1988. Snowfall was removed periodically (it was never allowed to build up more than 15 cm) to allow maximum penetration of the freezing front (Figure 76).

In late winter (March 1988), the east pit was loaded with a sand surcharge down its middle from east to west (Figure 77). The sand surcharge had a triangular shape with a 1-m wide base and a 0.5-m height. The intended purpose of the sand surcharge was to cause a surface channel to form which would gather surface thaw water and conduct it to the sand channels in the pits' dykes. To facilitate drainage through the sand channels in the dykes, copper pipe was inserted from the outside into the pit with an upward slope towards the water layer above the sludge. Plastic tubes that floated on the surface water were attached to the end of the copper pipes to drain surface thaw water by gravity.

A different drainage system was tested in spring of 1989. All pipes and tubes were removed from the sand channels and one channel on each pit was breached to form a V-cut. The bottom of the V-cut was lowered (either manually or by the eroding force of the drainage water) as the sludge surface dropped.

The east and west pits were seeded to reed canary grass and western dock on June 18, 1988. One half of each pit was seeded to each plant species. Seed, equivalent to 12 kg/ha, was mixed into dry peat and blown onto the sludge surface using a commercial insulation blower. An equal amount of seed (12 kg/ha) was distributed by hand evenly over the peat-seed mix already on the sludge surface and covered with another layer of dried peat. The peat and seed formed a layer approximately 2-cm thick and soaked up water from the surface of the sludge within 48 h after application.

In spring 1989 (May), 2 m^2 of an established stand of reed canary grass near Edmonton was excavated by hand to a depth of 20 cm and transported to the Alberta Environmental Centre for washing. The rhizomes were harvested and washed free of soil and detritus. They were then cut to lengths varying from 1 cm to 3 cm (all of which had at least one bud) and stored in moist vermiculite at 4°C to harden off. The cool conditions also prevented growth until they were planted in the east and west sludge pits at Mildred Lake on June 3, 1989. The sprigs were placed on the sludge surface at a density of 70 to 90 sprigs/m^2 and lightly poked below the surface.

6.3.2 Results

Both the east and west pits froze all the way to the bottom of the sludge. Figures 78 and 79 show the temperature profiles of the deepest thermocouples in each pit from November 1987 to June 1988. In both cases, the sludge on the bottom reached a temperature below 0°C by January 15, 1988, although there were considerable temperature fluctuations after that date. The lowest temperature recorded at the bottom was -2°C in the west pit in the first week of February. All other thermocouples in both pits, placed at levels above those reported in Figures 78 and 79, reached temperatures well below -2°C

Figure 76. Clearing snow from the frozen sludge surface.

Figure 77. Sand surcharge placed on the frozen surface of the east pit.

(Table 43). The temperature of the sludge nearest the surface (10-cm below the surface) fell to below -20°C in the coldest part of the winter.

Freezing and thawing oil sands sludge under field conditions in Fort McMurray caused approximately the same increase in solids as did laboratory or small-scale treatments. Starting from a solids content of 24% to 35%, one year of freeze-thaw yielded oil sands sludge of 41% to 53% solids (Table 44). A second year of freezing and thawing increased the solids content to 55% to 63%.

The impact of freezing and thawing on solids content depended on the depth of the layer. Surface sludge increased its solids content over one winter by about 25%, while the next winter and summer caused approximately another 5% to 15% increase (Table 44). Sludge in the deepest layer (150 cm October 1987; 90 cm July 1988, Table 44) showed an increase in solids content in the first year of less than 10%. By the end of the second winter, the solids content in this layer increased by approximately 25%.

The relationship between an increase in solids content and temperature is displayed in Figure 80. At the sludge surface, the minimum temperature over the first winter was -25°C, and the increase in solids content was 20%. At 90-cm depth, the minimum temperature was -3.4°C, and the solids content increased only 8%.

The east and west pits were filled with sludge from the same source. However, the initial sludge solids content in the east pit was lower than that in the west pit (Table 44). Over the 2 years of freezing and thawing, this reversed occasionally; there was no pattern for predicting which pit or depth would increase most rapidly in percent solids.

The frozen sludge thawed in spring 1988, and the water released from the sludge accumulated on the surface. The sand channels did not let the surface water drain; the sludge formed a "coating" over the sand, blocking the intended drainage path. The copper tubes driven through the sand channel were able to drain much of the first layer of thaw water, but as more water was released from the sludge and with the accumulation of water caused by summer precipitation, the tubes became blocked.

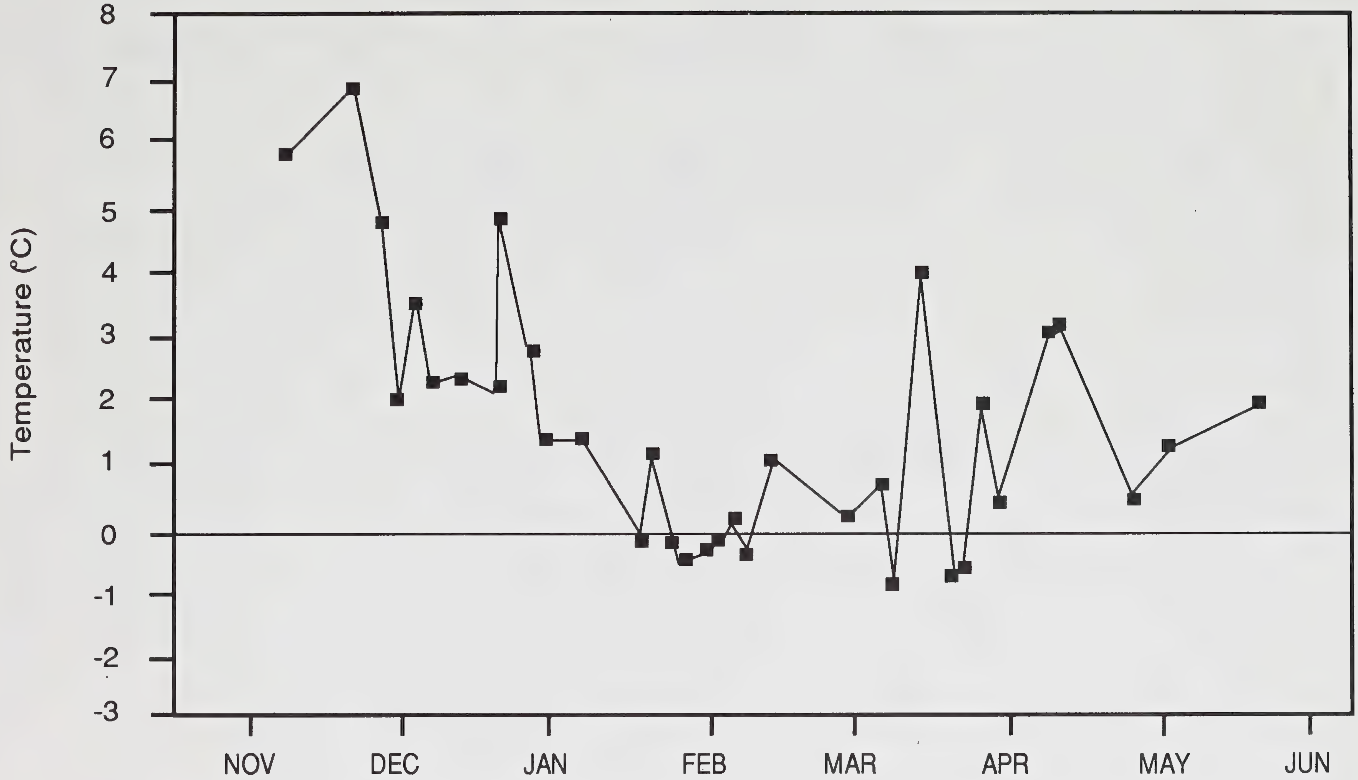


Figure 78. The temperature profile from Nov. 1987 to June 1988 of the deepest thermistor in the east pit.

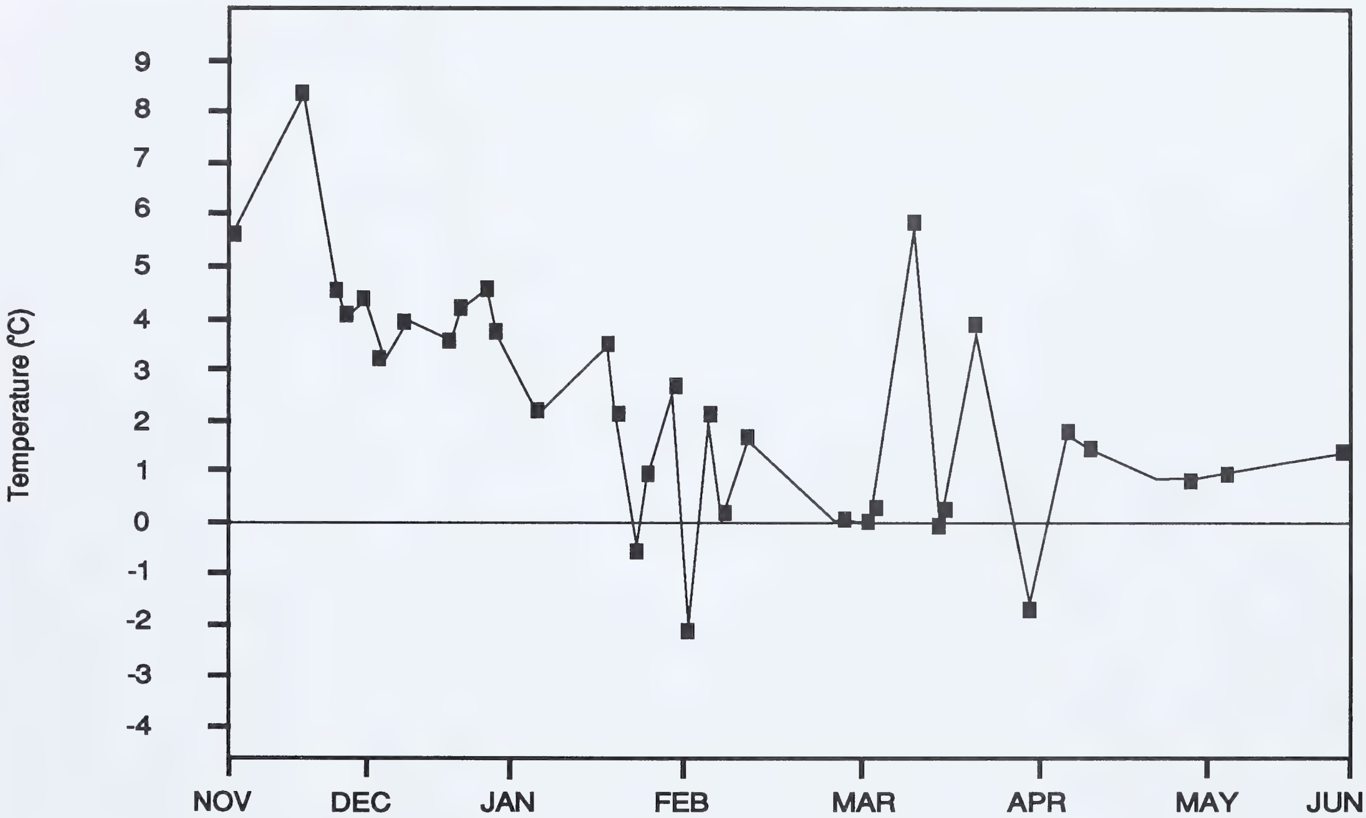


Figure 79. The temperature profile from Nov. 1987 to June 1988 of the deepest thermistor in the west pit.

Table 43. Minimum temperature (°C) by depth increment in both east and west oil sands sludge pits.

Depth (cm)	Pit	
	West	East
10	-20.3	-21.9
30	-13.0	-14.5
50	-11.6	-13.2
70	--	-7.7
80	-4.0	--
90	--	-3.4
100	-2.5	--
120	--	-2.1
130	-0.9	--
150	--	-1.1

There was excellent seed germination of both plant species on the sludge surface. However, the accumulating water prevented further plant development, except on the pit edges where drainage was better (Figure 81). Only reed canary grass survived and grew; the western dock plants perished shortly after germinating. Whenever drainage was adequate, the reed canary grass continued to grow.

After a full growing season (June to September 1988), the reed canary grass on the edges of the pit had dried the oil sands sludge to the point where it had sufficient strength to bear the weight of an 80-kg person (Figure 82). Some of the surface stability in this case resulted directly from the root and plant mat developed during reed canary grass growth. In those areas of the pit where plants did not grow, the surface strength of the sludge was too low to support a person.

Table 44. The effect of freezing and thawing over a 2-year period on the solids content (%) of oil sands sludge.

Depth (cm)	Pit	Sample Time			
		Oct '87[1]	July '88	June '89	Sept '89[2]
		(%)			
10	West	28.4	52.7	54.9	57.6
	East	23.9	48.8	59.5	62.7
30	West	29.2	46.2	53.5	55.2
	East	24.9	47.4	53.0	61.6
50	West	30.8	46.1	51.2	55.0
	East	26.1	47.3	54.1	59.5
70	West	32.3	46.4	--[3]	60.5
	East	29.7	43.9	--	59.7
90	West	33.0	41.3	C[4]	C
	East	29.4	43.1	C	C
110	West	33.7	C	C	C
	East	28.9	C	C	C
150	West	32.4	C	C	C
	East	35.7	C	C	C

[1] October 1987 was the original sampling date, immediately after the sludge was poured.
[2] September 1989 was the final sampling date.
[3] -- Not measured.
[4] C Consolidated sludge: the depth of the sludge at this time is considerably less than in the beginning.

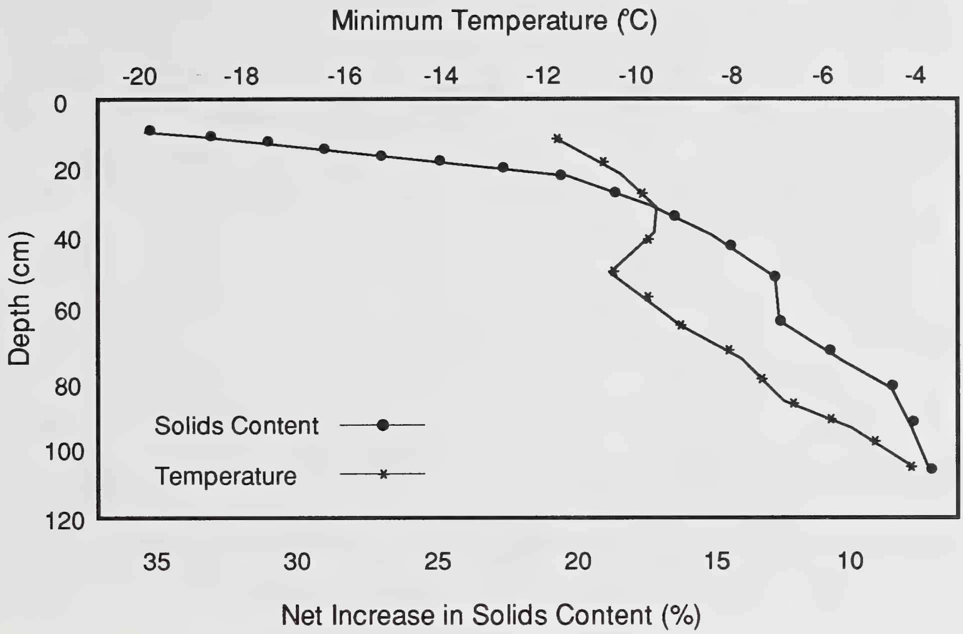


Figure 80. The relationship of increase in solids content to minimum temperature reached at various sludge depths (mean of east and west pits).

The sand placed on the bottom of the pits in ridges and the sand surcharge placed on the frozen sludge in the east pit did not create channels that drained the surface of the thawed sludge. After thawing, the sludge surface slumped slightly toward the middle regardless whether sand was placed above or below the original slope of the pit bottom.

In spring 1989, surface drainage was finally accomplished by cutting a deep notch in one of the sand channels in each pit (Figure 83). All the surface water that had accumulated as a result of the thaw immediately drained off the surface, and rainfall throughout summer 1989 followed the same route. In no case did the draining water

Figure 81. The accumulated water on the west pit with a failed drainage system. Note the reed canary grass on the pit edges.

carry liquid sludge (50% to 60% solids) with it; apparently, at that solids content, the sludge is sufficiently stable to resist erosion.

In winter of 1988-89, a pot experiment that tested three methods of sprig placement on sludge showed that both peat-covered sprigs and sprigs pushed just below the sludge surface established rapidly. Reed canary grass sprigs that were placed on the sludge surface and not covered with peat or those that were pushed several centimetres into the sludge did not grow or tiller. Therefore, the spring planting of 1989 (after two freeze-thaw periods) used reed canary grass rhizomes cut into small sections (sprigs) and pushed gently into the recently drained sludge surface.

Figure 82. Dewatered sludge planted to reed canary grass capable of bearing the weight of a person.

By mid-July 1989, approximately one-half the sprigs planted in early June had become established, they had achieved considerable growth, and had begun tillering (Table 45). Excellent plant cover can be established in sludge ponds by sprigging (Figure 84), even when the original sprigging rate was low. However, controlled environment tests showed that higher densities could be achieved if two criteria were met: (1) the density of the sprigs was greatly increased (300 to 400 sprigs/m^2), and (2) if sprigs were harvested from actively growing reed canary grass plants as opposed to dormant parent stock. It is also worth noting that sprigs established themselves and plants grew 10 cm to 20 cm in less than 6 weeks; reed canary grass established from seed on sludge can take 11 weeks to reach a comparable height (Section 6.2).

Figure 83. V-cut in sand channel (in background) to facilitate drainage (July 1989). (The grass on the pit edges originated from seed in 1988; the grass in the middle originated from sprigs placed in 1989).

6.3.3 Discussion

The process of freezing and thawing oil sands sludge caused nearly a 20% increase in solids content. First, this was shown under laboratory conditions; then, it was shown under outside conditions, using small volumes of sludge; it has been shown to hold true for field conditions with large volumes of sludge. However, there was a close relationship between the minimum temperature and the degree of dewatering. If the temperature reached only -1°C to -3°C, the solids content increase was seldom more than 10% (this happened on the bottom of a deep pool (2 m) of sludge where the overlying layers acted as insulation). If the temperature reached -20°C to -30°C, the solids content increased by 20% to 25%. To maximize water loss, therefore, it is advantageous to lower the temperature of the sludge as far as possible.

Table 45. The results of seeding both sludge pits with reed canary grass sprigs (July 17, 1989).

Pit	Plant number (#/m^2)	Plant height (cm)	Tiller number
West	45 to 54	10 to 15	4 to 5
East	36 to 45	10 to 20	2 to 4

Figure 84. Full stand of reed canary grass established on sludge pits (August 1990).

Water was released from the thawing sludge and accumulated on the surface. Drainage systems that had been tested and proven on a laboratory scale did not function well on a larger field scale. For example, surcharging the surface with sand did not cause a drainage channel when the sludge thawed. Instead, the sand dispersed throughout the sludge and eventually settled to the bottom. Bottom mounds made of sand did not result in surface drainage channels either. Apparently, the thawed sludge slumped enough to mask any effect of the bottom mounds. Finally, the west pit with a 4% slope on the bottom did not end up with a measurable slope on the surface.

In 1989, a more direct attack on surface drainage proved workable: a V-notch cut in the dyke to the level of the sludge surface allowed the water to drain out freely. The sludge surface was level enough that one opening provided total drainage for the entire pit. Furthermore, the oil sands sludge did not flow out; only water rushed through the dyke cutting the channel deeper as the thaw progressed and the sludge volume in the pit decreased. A simple, inexpensive drainage system for sludge has been identified. What is not known is the maximum area that could be drained by one V-channel on a very large (>1 ha) field scale.

Establishing plants early in the spring has been a problem since the inception of this work. Poor drainage, transplant shock, and dessication have all been identified as detrimental factors. This large pit experiment showed also that neither reed canary grass nor western dock would establish where drainage was poor. On the edges of the pit, where drainage was good, germination and growth of reed canary grass were excellent. (Western dock did not perform well even under these conditions.) For the first time, "sprigging", or planting by means of cut-up rhizomes, was tested on oil sands sludge. If the sprigs were dense enough, good plant stands were achieved in approximately one-half the time needed to get similar stands from seed. There was also some evidence that sprig establishment could be improved by using rhizomes cut from actively growing plants.

The combination of secure surface drainage and rapid plant establishment by sprigs offered the possibility of biological dewatering of oil sands sludge. The fact

that dewatered sludge (80% solids) is capable of supporting machinery or further sludge overboarding means the next studies should include operational and economic feasibility.

7.0 CONCLUSIONS

Two oil sands extraction plants in Fort McMurray, Alberta, producing approximately 200,000 barrels of synthetic crude oil per day, generate enormous volumes of by-products. Of particular concern is oil sands sludge, which comprises fine-grained materials suspended in water with a small amount of residual bitumen. Currently, the sludge is deposited in tailings ponds, occupying more than 29 km^2, where the mineral material consolidates to 30% solids in approximately 2 years. Annually, the two extraction plants produce 25 million cubic metres of sludge at 30% solids.

The low permeability of the partially consolidated sludge is caused by the fine size of the mineral matter (100% < 44 μm diameter; 50% < 2 μm diameter) and by the residual bitumen (3% to 6% of the dry weight solids) blocking the pores. The dispersed state of the colloidal clays (caused partly by the effects of sodium added to improve bitumen recovery) may also decrease the permeability. Low permeability causes low pore pressures within the consolidating sludge. Therefore, water release to the surface slows, and consolidation ceases when the solids content exceeds 30% to 35%.

The non-consolidating sludge cannot be stored forever above ground in tailings ponds because of: (1) the high cost of construction and maintenance; (2) the need to gain access to valuable reserves of oil sands immediately below the ponds; and (3) the environmental hazards, represented most obviously in the case of Suncor Inc. by the potential release of sludge and process water to the Athabasca River. From the beginning, the intended reclamation procedure for oil sands sludge was to "solidify, store in the mined out area, and reclaim to the original state" (Scott et al. 1985).

The technology for disposing of oil sands sludge must be inexpensive (<$1/$m^3$ according to J. Liu, Syncrude Canada Ltd., personal communication 23 July 1989), be feasible on a vast scale, and protective of the environment. Sludge disposal technology should be usable in summer and winter.

There are only two proven techniques for economically solidifying non-consolidating fines: wet coarse addition and drying. The first solves the problem of the lack of permeability by adding sufficient amounts of coarse-grained material, like

sand, to facilitate free drainage. The sand particles also provide the solid matrix that determines final consolidation volumes; the clays and silts occupy some of the large pore space between the sand particles. The second technique of solidification is drying by: (1) the provision of drainage, (2) evaporation and/or evapotranspiration, or (3) novel schemes, such as moisture absorption by desiccated, over-consolidated clays and shales (Dusseault et al. 1989). Often, techniques are combined to accomplish the solidification task more rapidly, more completely, or at lower cost.

Wet coarse addition, or adding sand, to dry out sludge has been the subject of intensive research at the Civil Engineering Department of the University of Alberta in Edmonton and the research scientists at Syncrude Canada Ltd. (Isaac 1986; Scott and Cymerman 1984; Scott et al. 1985). An abundant volume of sand is produced as a by-product of bitumen extraction, and mixing sand with sludge is relatively easy. The major limitations to the use of this technique are: (1) the large amounts of sand handled in the disposal of a small amount of fines (3:1 mixtures of sand:sludge are typical), which increases the cost of sludge disposal; (2) the unpredictability of the segregation of sand and sludge even when lime is added; and (3) the length of time needed for pore water pressure to decrease after the sand is added to obtain adequate surface stability. "Any deposition of sludge mixtures within the lease areas must meet the criteria of ... possessing sufficient shear strength in the short term to allow capping which usually means having a bearing capacity which will support mobile equipment" (Isaac 1986). Shear strength in excess of 100 kPa is required (Shaw 1984), and for 3:1 sand-sludge mixtures this represents approximately 85% solids (Isaac 1986).

The best way for achieving shear strengths in excess of 100 kPa (equivalent to a void ratio of less than 1), is to relieve excess pore pressure by drains. However, there are no studies of sand-sludge mixtures that incorporate drainage as an additional mechanism of dewatering.

G.J. Sparrow and colleagues at the CSIRO Institute of Energy and Earth Resources in Port Melbourne, Victoria, Australia (Sparrow 1978; Sparrow 1981; Sparrow and Ihle 1978; Ihle et al. 1983), used previously published theories on the movement of

water into porous media (i.e., soil) to develop a technique for calculating the equilibrium values of sedimentation and drainage of sludges. When applied to mixtures of oil sands and sludges in the laboratory, this technique proved to be simple and relatively easy to manipulate mathematically. Above all, the CSIRO technique was flexible; it was possible to change operating conditions, such as sand:sludge ratios and lime concentration, or initial and final solids contents before and after dewatering.

Using the CSIRO technique, it was possible to estimate the contribution that drainage would make to dewatering sand-sludge mixtures deposited at several depths. Two meters of sand-sludge mixture at 3:1 ratio would dewater from 55% solids to 85% solids in 50 months using bottom drainage as well as surface evaporation. Dewatering would also lead to consolidation of the sand-sludge mixture: more than 40% of the original height of the pool (or stack) would be lost as it was dewatered. Since infinite or finite strain analysis (Isaac 1985) had not been used to calculate the dewatering potential of sand-sludge mixtures, there was no way of estimating the theoretical soundness of the CSIRO approach. In any case, the extra cost of providing drainage underneath the sand-sludge stack, without reducing the time needed for complete dewatering to less than 1 year, reduced the feasibility of this approach.

An interesting footnote to the results reported on the dewatering calculations was that lime not only successfully kept sand and sludge in suspension (if rigorous quality control of the proportions and concentrations was exercised), it enhanced the permeability by 10 to 40-fold. Still, the permeability was not increased to the point where sedimentation or drainage would economically dewater sand-sludge mixtures.

A 2-m depth of sand-sludge mixture at 55% solids has 980 mm of water that must be removed to achieve 85% solids. The CSIRO calculation showed that more than one-third (360 mm) would be lost to evaporation, even when evaporation was assumed to cease after one summer. Since water loss at the surface of a soil is increased by vegetation through transpiration, the possibility of using plants to shorten the dewatering time of sand-sludge mixtures to less than 1 year was considered next.

Incorporating plants into the dewatering operation meant that surface drainage of the sand-sludge mixture was critical, because all outside sources of water would have to be eliminated to maximize the water loss. The ideal plants would have: an ability to germinate and grow under waterlogged conditions; a tolerance for dry conditions, as the sand-sludge lost water and consolidated; a deep, fast growing, root system; a capability of transpiring large amounts of water; and a tolerance of the special conditions of sand-sludge, namely, medium salinity (electrical conductivity equal to 4 dS/m), high pH (8.2), cold temperatures, and small amounts of residual bitumen.

From a survey of 53 candidate plant species, two were identified that met all of these criteria. They were: reed canary grass (Phalaris arundinacea) and western dock (Rumex occidentalis). In a greenhouse experiment under conditions that simulated those of Fort McMurray, the two plants grew prolifically from small transplants in oil drum-lysimeters and dewatered a 3:1 sand-sludge mixture from 55% to 85% solids to a depth of 80-cm in 11 weeks. During that time, these two species transpired 511 mm of water. Furthermore, they left behind consolidated sand-sludge mixtures that had shear strengths in excess of 100 kPa to the bottom of the lysimeter. The sand-sludge mixtures consolidated to 69% of their original depths.

When these two plant species were used under field conditions (Fort McMurray), they were not successful. Several times they failed to establish themselves from transplants. This was probably caused by shock, but the inability of the experimenters to control the surface drainage and excess ammonium (NH_4) added as fertilizer no doubt contributed to these failures. Establishment from seed was not successful either. Surface drainage and excess ammonium inhibited their growth when the surface water was controlled plants could be started from seed on sand-sludge mixtures in the field if a mulch cover was used to prevent rapid dessication.

The fertilizer requirements of reed canary grass (which was the better choice of plants) on sand-sludge mixtures included nitrogen, phosphorus, and potassium. The largest production of above-ground biomass and root weight, the largest leaf area, the

most tillers per plant, and the greatest height were achieved with 120 ppm of ammonium nitrate, 40 ppm phosphorus, and 50 ppm potassium.

Plants had to be established rapidly to allow biological dewatering to operate in a short summer season. The temperature, light regime, and oxygen supply proved to be the important factors governing the germination of native and agricultural plants, as they adapted to the wet environment of sand sludge mixtures or pure sludge at 50% to 60% solids. Rumex occidentalis, or western dock, proved to be the most tolerant of low temperatures and varied light regimes. Seed taken from one-year-old standing western dock plants, fully maintained its capacity to germinate. The most promising agricultural species were reed canary grass and meadow foxtail, but they germinated more slowly than western dock, especially when ambient temperatures were less than 18°C. There was no need to add mulch to aid seed germination on sand-sludge mixtures. Cattails (Typha spp.) germinated only when they were immersed in water; they were damaged by some constituent of the sludge (probably the salt or residual bitumen), even after they had germinated and grown to 20-cm height.

A simple laboratory test of freezing and thawing sludge led to a further development in dewatering technology. Beginning with pure (no sand added) oil sands sludge at 30% solids, one cycle of freezing and thawing caused a 25% loss of water, leaving sludge at 55% solids. This corresponded approximately to the same solids content as was achieved by mixing three parts sand to one part sludge. Also, the cost was an order of magnitude less because the freeze-thaw process is a natural phenomenon of a northern Alberta winter. Furthermore, sludge without sand needed to reach only 80% solids, 5% less than a sand-sludge mixture, to have sufficient strength (> 100 kPa) to support machine traffic or overboarding.

Since mature sludge, found at the bottom of the tailings ponds, contains approximately 30% solids, a new alternative for sludge dewatering on a larger scale was pursued. Research was directed to: demonstrating the effectiveness of freeze-thaw dewatering in laboratory experiments and on a field scale; investigating ways for increasing the amount of sludge that could be frozen and thawed in one winter; devising

an inexpensive method for removing water accumulating on the sludge surface after the thaw; identifying a technique for establishing plants on sludge which had been frozen and thawed so that the dewatering process could be completed; and quantifying the amount of volume reduction that took place in both pure sludge and sand-sludge dewatering.

Subsequent cycles of freezing and thawing sludge under laboratory conditions led to much smaller amounts of dewatering. The water collected from the sludge after thawing had a high dissolved solids content (E.C. = 4.1 dS/m), high turbidity, and a relatively high pH (8.4). It was non-toxic, however, in a Microtox assay.

The process of freezing and thawing oil sand sludge to remove water was shown to work as well on a pilot scale (45 L) as on a laboratory scale. The amount of water lost by freezing and thawing depended on the initial solids content of the sludge; the sludge suspensions with the lowest solids content dewatered to the greatest extent. There was an exponential decrease in the amount of water released as pre-freezing solids content increased. Consecutive freeze-thaw treatments (to a maximum of three) were capable of producing sludge with 60% solids. The Neuman-Stefan proportionality coefficients, needed to estimate the depth of sludge that could be frozen over winter, ranged from 2.59 for sludge at 16% solids to 3.41 for sludge at 45% solids.

The dewatering of sludge by freezing and thawing was shown to operate under field conditions as well as in the laboratory. Sludge solids content increased from 30% to 55% solids after undergoing freezing and thawing in unlined pits at both the Alberta Environmental Centre (central Alberta) and at the Syncrude Canada Ltd. plant at Mildred Lake (northern Alberta). The water rose to the sludge surface as soon as it thawed.

The depth of sludge freezing was limited under field conditions by the rate of frost penetration. The high water content of sludge, when compared to unsaturated soil, slowed the advance of the freezing front. When snow, the major insulator in winter, was removed from the sludge surface at Mildred Lake, the freezing extended to approximately 165 cm. If the snow was not removed, freezing was limited to 30 cm (G. Lesko, Syncrude Canada Ltd., personal communication).

Layered freezing a few centimetres thick, was tested under pilot-plant conditions (carried out in oil drums). Layered freezing resulted in a larger loss of water from sludge (20%) than static freezing (14%). However, layered freezing was not faster than static freezing. (This research was done under controlled conditions using large, walk-in freezers.) When a new layer was poured on top of the previously frozen sludge, the entire mass of sludge absorbed heat from the fresh layer. Before carrying out this experiment, it was expected that most of the heat contained in the warm sludge layer on top would be transferred into the open air.

Sego et al. (1993) report that 3.5 to 4.0 m of oil sands sludge can be frozen, using layered freezing, during an average winter at Fort McMurray. No comparisons were made between rates for static and layered freezing.

Laboratory and pilot-plant experiments showed that frozen sludge thawed at the rate of 1 cm/5 h. Under these conditions, as much as 5 m of frozen sludge would thaw in 100 days of warm spring and summer weather. However, Sego et al. (1993) demonstrated that only 3 m of frozen sludge thawed during the spring and summer season at Fort McMurray. Thus, the amount of oil sands sludge that can be treated by freeze-thaw methods at Fort McMurray is restricted by the climatic controls on thawing.

Thaw water from the oil sands sludge rose to the surface almost immediately. Approximately 15 cm of water accumulated on the surface for every metre of sludge that was frozen and thawed. The thaw water had to be removed to allow further desiccation of sludge. If left on the surface, the thaw water inhibited sludge drying by evaporation and vegetation establishment. Neither reed canary grass nor western dock could be established from seed or transplants if water was allowed to accumulate on the sludge surface. The sludge surface was fluid and unstable as a transplant medium for young seedlings; they tipped over into the sludge and died under the windy conditions of field trials. Seeds of both plant species were detached from the sludge surface and were lost in the pooled water. It is also probable that pooled water severely restricted aeration at the plant root and caused seedling death by oxygen starvation.

The simplest way for removing water was to pour sludge on a slight slope. (It was estimated that a 2% slope would be sufficient on a field scale.) Measurements made from slope tables in the laboratory demonstrated that sludge at 35% solids (or a viscosity of more than 2,660 centipoise) would maintain a 2% slope. Simulated rainfall (9.4 mm over 2 min) did not affect slope stability. Lime amendments were used to increase sludge viscosity. Sludge at 30% solids (the solids content of much of the sludge at the bottom of the tailings ponds) held a 2% slope if more than 1,000 ppm lime was added, but his would increase costs considerably. Furthermore, lime-amended sludge lost viscosity over time; any apparent gain in slope stability could be lost over the freeze-thaw cycle.

On a small scale (0.5 m^3), surface drainage was engineered into the thawing sludge by laying down surcharges of sand when the sludge surface was frozen. However, when this method was tested on a pilot scale (100 m^3) the sand slumped through the thawing sludge, no surface impression was left, and thaw water did not run off.

Under field conditions, a simple V-notch cut in the side of the dyke holding the thawing sludge drained all the water that had accumulated on a 50-m^2 surface over one winter. The draining water did not erode the thawed sludge at 55% solids content.

Establishing plants on sludge, even when the surface had been drained, was not simple. Conditions that fluctuated from a semi-aquatic environment (as the thaw water rose to the surface) to a dry, hard surface with wet, soft sludge underneath (as the sludge was progressively dewatered from top to bottom), made plant establishment difficult. Transplants, grown from seed in the greenhouse, grew well on oil sands sludge if surface water was drained, but the transplanting was expensive. Reed canary grass and western dock was started from seed on surface-drained sludge when mulch was used to protect against excessive drought in the initial stages. However, the cool weather in Fort McMurray in early June (the first available seeding date) and the residual cold from the thawing sludge, lengthened the establishment time so that very little evapotranspiration

occurred before September. By October, the first frost occurred and the plants had contributed almost nothing to the dewatering cycle in the first year.

Starting reed canary grass from sprigs--small sections of rhizome capable of developing into a complete plant--accelerated plant establishment on the thawing sludge. Operationally, sprig production can be mechanized and the cost can be minimized. About half the reed canary grass sprigs thrown out onto the sludge surface (the sprigs were not inserted; they sank into the sludge a few millimetres under their own weight) established immediately. By July, the plants originating from sprigs were 20 cm in height and had tillered profusely. For optimal plant density, 150-200 plants/m^2 were required. At the end of the second summer of dewatering, reed canary grass plants started from sprigs were 100-cm tall and in full seed production.

As the sludge was dewatered, it progressively decreased in volume. Over the first winter of a field trial at Fort McMurray, the sludge increased in solids content from 30% to 55% solids; the volume reduction due to this water loss was 67%, i.e., only one-third the original volume of sludge remained after the first winter. By the end of the third winter, the solids content of the pure sludge was 82% and the volume had decreased by four-fifths.

Dewatering by freezing and thawing worked as well, or better, on sand-sludge mixtures as it did on pure sludge. In a field experiment at Fort McMurray, 3:1 sand-sludge mixtures at 55% solids, poured 2-m deep into grain bins, dewatered to 80% solids in one winter. Since the desirable solids content for a sand-sludge mixture is 85%, one freeze-thaw cycle was nearly sufficient to complete the dewatering process. Sand-sludge mixtures froze faster and deeper than did pure sludge, probably because of a higher, initial solids content. The same field experiment showed that sand-sludge mixtures decreased in volume by 45% as dewatering proceeded over the freeze-thaw cycle.

Pure sludge, like sand-sludge mixtures, was extremely deficient in nutrient elements; it contained 7 ppm, 2 ppm, and 13 ppm of nitrogen, phosphorus, and potassium, respectively. Adding fertilizer to pure sludge prior to freezing did not increase the solids

content above a control to which fertilizer was not added. However, almost 50% of the nitrate nitrogen and 33% of the phosphorus and potassium added to the sludge before freezing was lost to the thaw water that drained from the surface. Fertilizer amendments could be expensive if added before freezing and could contribute to a major pollution load in the drainage water.

Reed canary grass cultivated on pure sludge after freezing and thawing quickly turned yellow and stopped growing if N, P, or K was not added. As little as 100 ppm N, 30 ppm P, and 150 ppm K were sufficient to achieve optimal reed canary grass growth on pure sludge over two harvest periods in the greenhouse (73 days). Plant biomass production increased most when nitrogen and phosphorus were added. However, 300 ppm N was excessive, causing a decrease in biomass and a general lack of vigour in the plants.

8.0 RECOMMENDATIONS

1. Investigate the physical and engineering properties of undisturbed samples of oil sands sludge after freezing and thawing, especially in regard to the properties governing water movement and sludge compressibility. Successful dewatering of oil sands sludge by freezing and thawing is associated with unimpeded water movement to the surface. Drainage of water through the underlying material is minimal. The sludge structure that results from freezing and thawing and allows the release of water to the surface is unknown. The stability of the structure is also unknown, but may have a major impact on drainage when the sludge is remoulded. The few tests conducted on sludge that has been frozen and thawed have used disturbed samples; only the study of undisturbed samples can provide a description of sludge structure, capable of releasing large amounts of water quickly to the surface. The protection and management of this structure may be the key to dewatering on a field scale.

2. Measure the effective shear strength properties of oil sands sludge that has been frozen and thawed and dewatered to different solids content. Preliminary tests in the laboratory and small field tests have shown that sludge, which has undergone freezing and thawing and contains approximately 50% solids, can be moulded into ditches, so that water could be drained off. Shear strength governs the permanent angles of repose of oil sands sludge, which will determine the stability of the drainage ditches. The depth of the water table in the ditches and under the dykes may be other manageable factors governing the stability of sludge-drainage systems.

3. Design and test passive surface-drainage systems for removing rainfall or water that accumulates as a result of thawing. After measuring the nature and rate of sludge consolidation during freezing and thawing (Recommendation 1) and the effective shear strength of frozen and thawed sludge (Recommendation 2), workable drainage systems can be designed on a large scale. The limiting angle of repose, the nature of slumping, and the resistance to erosion are criteria affecting the design of operational drainage systems. From the design will come the depth and spacing of the surface ditches and the pattern of their distribution.

4. Identify a method for economically producing large quantities of reed canary grass sprigs. One hundred hectares of oil sands sludge undergoing dewatering by freeze-thaw and vegetative evapotranspiration needs approximately two million metres of roots to serve as sprigs (100 ha x 10,000 m^2 x 200 sprigs/m^2 x 1 cm/sprig). The rhizomes of reed canary grass are prolific and relatively easy to harvest, if grown on suitable material, but a sprig-producing facility of this size has not been developed anywhere in the world.

5. Evaluate methods for storing sprigs over several months without losing viability. The quantity of sprigs necessary for biological dewatering probably means that sprig production will occur in the agriculturally favourable zones of Alberta, and the sprigs will be transported to Fort McMurray when needed in spring. The limitations to storage and transport of living roots are unknown.

6. Identify, procure, and evaluate "flotation" equipment that can effectively operate on the semi-viscous surface of freeze-thaw sludge without damaging the sludge's ability to be dewatered. This set of motor-driven equipment will be used to "farm" sludge as the second step toward dessication. The equipment will be used to excavate shallow ditches, till the sludge surface to prevent crusting, fertilize, and plant sprigs.

7. Design a sludge-freezing process that prevents snow from accumulating on the sludge surface, thereby optimizing the environment for freezing and thawing. Part of the snowfall might be used as part of the containment system to replace walls or dykes made from soil, overburden, or sand. Snow walls could be designed to melt in spring as the sludge thaws, leaving a stabilized block of thawed sludge which is also self-draining.

8. Test layered freezing on a large field scale. It has been calculated that thin layers of sludge, frozen in as few as 24 to 48 h, will lead to a tripling or quadrupling of the total depth of sludge that can be frozen over one winter. The ability to handle much larger volumes of sludge in less area is an important requirement of field scale dewatering technology. Parameters such as layer thickness, freezing time, pumping rate

have not been optimized for oil sands sludge. Layered freezing also needs a simple system to deliver fluid sludge over the entire winter.

9. Determine the variability of tailings pond sludge at the two major oil sands extraction plants by using of a systematic sampling program, including a chemical and physical (including engineering properties) analysis, and a statistical evaluation. Each separate tailings pond should be sampled in several randomly chosen locations at several depths. Future work on the dewatering of oil sands sludges depends on a detailed knowledge of the relationship between the sludge properties in a sample and those of the entire sludge mass (or population).

10. Investigate the bearing strength of partially dewatered sludge (70% solids) that has a full cover of reed canary grass established on the surface. Under the most unfavourable climatic conditions (high rainfall, low insulation), it may be possible to dewater sludge by freezing, thawing, and evapotranspiration to 70% solids over one winter and one summer. Traffic and sludge overboarding are possible on materials having a bearing strength of 100 kPa or 80% solids. But reed canary grass has an extensive root system that increases shear strength, over and above its contribution to dewatering, may be possible to improve the dewatering process by using the enhanced shear strength of sludge, woven together with reed canary grass rhizomes.

11. Evaluate the economics of dewatering 3:1 sand-sludge mixtures using only freezing and thawing. This report contains data from an experiment at Fort McMurray showing that 3:1 sand-sludge mixtures, starting at 50% solids, will dewater to 80% solids in one winter, without vegetative growth. Since the desired solids content for these mixtures is 85%, it may be possible to complete the dewatering process without vegetation.

12. Test the efficacy of adding lime to sand-sludge mixtures to prevent sand segregation on a field scale. Most of the time, lime added at 1,000 ppm prevented sand segregation in the laboratory, but field operations cause the ratio of sand to sludge, the total solids content, and lime content to vary greatly. The operational use of lime, as a stabilizer against segregation, will depend on its efficacy under actual field conditions.

13. Test the feasibility of in-situ sludge dewatering. Partially dewatered sludge, higher in solids and density as a result of freezing, could replace mature sludge at the bottom of the tailings pond. After the pond has frozen over, sludge could be pumped from the bottom and frozen on the ice above. The sludge and ice supporting it will melt in spring. The sludge will sink to the bottom owing to its higher density and displace less dense (lower solids content) sludge. The same program could be followed over several winters, until all the sludge reaches 55% to 60% solids. The water above would contain less than 1% solids and could be used for recycling within the extraction plant or be treated and released. After removing the water, the partially dewatered sludge could be fully dewatered using evaporation and/or biological means.

14. Evaluate the ability of a large sludge pond to form a dry "skin" at the surface, following dewatering, that would allow a water cap to be placed on top. The skin would act as a barrier to the mixing of sludge and the water cap in a "sludge-bottom lake".

9.0 LITERATURE CITED

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RECLAMATION RESEARCH REPORTS

1. **RRTAC 79-2: Proceedings: Workshop on Native Shrubs in Reclamation. P.F. Ziemkiewicz, C.A. Dermott and H.P. Sims (Editors). 104 pp. No longer available.**

The Workshop was organized as the first step in developing a Native Shrub reclamation research program. The Workshop provided a forum for the exchange of information and experiences on three topics: propagation; outplanting; and, species selection.

2. **RRTAC 80-1: Test Plot Establishment: Native Grasses for Reclamation. R.S. Sadasivaiah and J. Weijer. 19 pp. No longer available.**

The report details the species used at three test plots in Alberta's Eastern Slopes. Site preparation, experimental design, and planting method are also described.

3. **RRTAC 80-2: Alberta's Reclamation Research Program - 1979. Reclamation Research Technical Advisory Committee. 22 pp. No longer available.**

This report describes the expenditure of $1,190,006 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

4. **RRTAC 80-3: The Role of Organic Compounds in Salinization of Plains Coal Mining Sites. N.S.C. Cameron et al. 46 pp. No longer available.**

This is a literature review of the chemistry of sodic mine spoil and the changes expected to occur in groundwater.

5. **RRTAC 80-4: Proceedings: Workshop on Reconstruction of Forest Soils in Reclamation. P.F. Ziemkiewicz, S.K. Takyi and H.F. Regier (Editors). 160 pp. $10.00**

Experts in the field of forestry and forest soils report on research relevant to forest soil reconstruction and discuss the most effective means of restoring forestry capability of mined lands.

6. **RRTAC 80-5: Manual of Plant Species Suitability for Reclamation in Alberta. L.E. Watson, R.W. Parker and D.F. Polster. 2 vols, 541 pp. No longer available; replaced by RRTAC 89-4.**

Forty-three grass, fourteen forb, and thirty-four shrub and tree species are assessed in terms of their suitability for use in reclamation. Range maps, growth habit, propagation, tolerance, and availability information are provided.

7. **RRTAC 81-1: The Alberta Government's Reclamation Research Program - 1980. Reclamation Research Technical Advisory Committee. 25 pp. No longer available.**

This report describes the expenditure of $1,455,680 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

8. **RRTAC 81-2: 1980 Survey of Reclamation Activities in Alberta. D.G. Walker and R.L. Rothwell. 76 pp. $10.00**

This survey is an update of a report prepared in 1976 on reclamation activities in Alberta, and includes research and operational reclamation, locations, personnel, etc.

9. **RRTAC 81-3: Proceedings: Workshop on Coal Ash and Reclamation. P.F. Ziemkiewicz, R. Stein, R. Leitch and G. Lutwick (Editors). 253 pp. $10.00**

Presents nine technical papers on the chemical, physical, and engineering properties of Alberta fly and bottom ashes, revegetation of ash disposal sites, and use of ash as a soil amendment. Workshop discussions and summaries are also included.

10. **RRTAC 82-1: Land Surface Reclamation: An International Bibliography. H.P. Sims and C.B. Powter. 2 vols, 292 pp. $10.00**

Literature to 1980 pertinent to reclamation in Alberta is listed in Vol. 1 and is also on the University of Alberta computing system (in a SPIRES database called RECLAIM). Vol. 2 comprises the keyword index and computer access manual.

11. **RRTAC 82-2: A Bibliography of Baseline Studies in Alberta: Soils, Geology, Hydrology and Groundwater. C.B. Powter and H.P. Sims. 97 pp. $5.00**

This bibliography provides baseline information for persons involved in reclamation research or in the preparation of environmental impact assessments. Materials, up to date as of December 1981, are available in the Alberta Environment Library.

12. **RRTAC 82-3: The Alberta Government's Reclamation Research Program - 1981. Reclamation Research Technical Advisory Committee. 22 pp. No longer available.**

This report describes the expenditure of $1,499,525 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

13. **RRTAC 83-1: Soil Reconstruction Design for Reclamation of Oil Sand Tailings. Monenco Consultants Ltd. 185 pp. No longer available**

Volumes of peat and clay required to amend oil sand tailings were estimated based on existing literature. Separate soil prescriptions were made for spruce, jack pine, and herbaceous cover types. The estimates form the basis of field trials (See RRTAC 92-4).

14. **RRTAC 83-2: The Alberta Government's Reclamation Research Program - 1982. Reclamation Research Technical Advisory Committee. 25 pp. No longer available.**

This report describes the expenditure of $1,536,142 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

15. **RRTAC 83-3: Evaluation of Pipeline Reclamation Practices on Agricultural Lands in Alberta. Hardy Associates (1978) Ltd. 205 pp. No longer available.**

Available information on pipeline reclamation practices was reviewed. A field survey was then conducted to determine the effects of pipe size, age, soil type, construction method, etc. on resulting crop production.

16. **RRTAC 83-4: Proceedings: Effects of Coal Mining on Eastern Slopes Hydrology. P.F. Ziemkiewicz (Editor). 123 pp. $10.00**

Technical papers are presented dealing with the impacts of mining on mountain watersheds, their flow characteristics, and resulting water quality. Mitigative measures and priorities were also discussed.

17. **RRTAC 83-5: Woody Plant Establishment and Management for Oil Sands Mine Reclamation. Techman Engineering Ltd. 124 pp. No longer available.**

This is a review and analysis of information on planting stock quality, rearing techniques, site preparation, planting, and procedures necessary to ensure survival of trees and shrubs in oil sand reclamation.

18. **RRTAC 84-1: Land Surface Reclamation: A Review of the International Literature. H.P. Sims, C.B. Powter and J.A. Campbell. 2 vols, 1549 pp. $20.00**

Nearly all topics of interest to reclamationists including mining methods, soil amendments, revegetation, propagation and toxic materials are reviewed in light of the international literature.

19. **RRTAC 84-2: Propagation Study: Use of Trees and Shrubs for Oil Sand Reclamation. Techman Engineering Ltd. 58 pp. $10.00**

This report evaluates and summarizes all available published and unpublished information on large-scale propagation methods for shrubs and trees to be used in oil sand reclamation.

20. **RRTAC 84-3: Reclamation Research Annual Report - 1983. P.F. Ziemkiewicz. 42 pp. $5.00**

This report describes the expenditure of $1,529,483 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas and describes the projects funded under each program.

21. **RRTAC 84-4: Soil Microbiology in Land Reclamation. D. Parkinson, R.M. Danielson, C. Griffiths, S. Visser and J.C. Zak. 2 vols, 676 pp. $10.00**

This is a collection of five reports dealing with re-establishment of fungal decomposers and mycorrhizal symbionts in various amended spoil types.

22. **RRTAC 85-1: Proceedings: Revegetation Methods for Alberta's Mountains and Foothills. P.F. Ziemkiewicz (Editor). 416 pp. $10.00.**

Results of long-term experiments and field experience on species selection, fertilization, reforestation, topsoiling, shrub propagation and establishment are presented.

23. **RRTAC 85-2: Reclamation Research Annual Report - 1984. P.F. Ziemkiewicz. 29 pp. No longer available.**

This report describes the expenditure of $1,320,516 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas and describes the projects funded under each program.

24. **RRTAC 86-1: A Critical Analysis of Settling Pond Design and Alternative Technologies. A. Somani. 372 pp. $10.00**

The report examines the critical issue of settling pond design, and sizing and alternative technologies. The study was co-funded with The Coal Association of Canada.

25. **RRTAC 86-2: Characterization and Variability of Soil Reconstructed after Surface Mining in Central Alberta. T.M. Macyk. 146 pp. No longer available.**

Reconstructed soils representing different materials handling and replacement techniques were characterized, and variability in chemical and physical properties was assessed. The data obtained indicate that reconstructed soil properties are determined largely by parent material characteristics and further tempered by materials handling procedures. Mining tends to create a relatively homogeneous soil landscape in contrast to the mixture of diverse soils found before mining.

26. **RRTAC 86-3: Generalized Procedures for Assessing Post-Mining Groundwater Supply Potential in the Plains of Alberta - Plains Hydrology and Reclamation Project. M.R. Trudell and S.R. Moran. 30 pp. $5.00**

In the Plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifers.

27. **RRTAC 86-4: Geology of the Battle River Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze, R. Li, M. Fenton and S.R. Moran. 86 pp. $10.00**

This report summarizes the geological setting of the Battle River study site. It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

28. **RRTAC 86-5: Chemical and Mineralogical Properties of Overburden: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 71 pp. $10.00**

This report describes the physical and mineralogical properties of overburden materials in an effort to identify individual beds within the bedrock overburden that might be significantly different in terms of reclamation potential.

29. **RRTAC 86-6: Post-Mining Groundwater Supply at the Battle River Site: Plains Hydrology and Reclamation Project. M.R. Trudell, G.J. Sterenberg and S.R. Moran. 49 pp. $5.00**

The report deals with the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is in the Battle River Mining area in east-central Alberta.

30. **RRTAC 86-7: Post-Mining Groundwater Supply at the Highvale Site: Plains Hydrology and Reclamation Project. M.R. Trudell. 25 pp. $5.00**

This report evaluates the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is the Highvale mining area in west-central Alberta.

31. **RRTAC 86-8: Reclamation Research Annual Report - 1985. P.F. Ziemkiewicz. 54 pp. $5.00**

This report describes the expenditure of $1,168,436 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas and describes the projects funded under each program.

32. **RRTAC 86-9: Wildlife Habitat Requirements and Reclamation Techniques for the Mountains and Foothills of Alberta. J.E. Green, R.E. Salter and D.G. Walker. 285 pp. No longer available.**

This report presents a review of relevant North American literature on wildlife habitats in mountain and foothills biomes, reclamation techniques, potential problems in wildlife habitat reclamation, and potential habitat assessment methodologies. Four biomes (Alpine, Subalpine, Montane, and Boreal Uplands) and 10 key wildlife species (snowshoe hare, beaver, muskrat, elk, moose, caribou, mountain goat, bighorn sheep, spruce grouse, and white-tailed ptarmigan) are discussed. The study was co-funded with The Coal Association of Canada.

33. **RRTAC 87-1: Disposal of Drilling Wastes. L.A. Leskiw, E. Reinl-Dwyer, T.L. Dabrowski, B.J. Rutherford and H. Hamilton. 210 pp. No longer available.**

Current drilling waste disposal practices are reviewed and criteria in Alberta guidelines are assessed. The report also identifies research needs and indicates mitigation measures. A manual provides a decision-making flowchart to assist in selecting methods of environmentally safe waste disposal.

34. **RRTAC 87-2: Minesoil and Landscape Reclamation of the Coal Mines in Alberta's Mountains and Foothills. A.W. Fedkenheuer, L.J. Knapik and D.G. Walker. 174 pp. No longer available.**

This report reviews current reclamation practices with regard to site and soil reconstruction and re-establishment of biological productivity. It also identifies research needs in the Mountain-Foothills area. The study was co-funded with The Coal Association of Canada.

35. **RRTAC 87-3: Gel and Saline Drilling Wastes in Alberta: Workshop Proceedings. D.A. Lloyd (Compiler). 218 pp. No longer available.**

Technical papers were presented which describe: mud systems used and their purpose; industrial constraints; government regulations, procedures and concerns; environmental considerations in waste disposal; and toxic constituents of drilling wastes. Answers to a questionnaire distributed to participants are included in an appendix.

36. **RRTAC 87-4: Reclamation Research Annual Report - 1986. 50 pp. No longer available.**

This report describes the expenditure of $1,186,000 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas and describes the projects funded under each program.

37. **RRTAC 87-5: Review of the Scientific Basis of Water Quality Criteria for the East Slope Foothills of Alberta. Beak Associates Consulting Ltd. 46 pp. $10.00**

The report reviews existing Alberta guidelines to assess the quality of water drained from coal mine sites in the East Slope Foothills of Alberta. World literature was reviewed within the context of the East Slopes environment and current mining operations. The ability of coal mine operators to meet the various guidelines is discussed. The study was co-funded with The Coal Association of Canada.

38. **RRTAC 87-6: Assessing Design Flows and Sediment Discharge on the Eastern Slopes. Hydrocon Engineering (Continental) Ltd. and Monenco Consultants Ltd. 97 pp. $10.00**

The report provides an evaluation of current methodologies used to determine sediment yields due to rainfall events in well-defined areas. Models are available in Alberta to evaluate water and sediment discharge in a post-mining situation. SEDIMOT II (Sedimentology Disturbed Modelling Techniques) is a single storm model that was developed specifically for the design of sediment control structures in watersheds disturbed by surface mining and is well suited to Alberta conditions. The study was co-funded with The Coal Association of Canada.

39. **RRTAC 87-7: The Use of Bottom Ash as an Amendment to Sodic Spoil. S. Fullerton. 83 pp. No longer available.**

The report details the use of bottom ash as an amendment to sodic coal mine spoil. Several rates and methods of application of bottom ash to sodic spoil were tested to determine which was the best at reducing the effects of excess sodium and promoting crop growth. Field trials were set up near the Vesta mine in East Central Alberta using ash readily available from a nearby coal-fired thermal generating station. The research indicated that bottom ash incorporated to a depth of 30 cm using a subsoiler provided the best results.

40. **RRTAC 87-8: Waste Dump Design for Erosion Control. R.G. Chopiuk and S.E. Thornton. 45 pp. $5.00**

This report describes a study to evaluate the potential influence of erosion from reclaimed waste dumps on downslope environments such as streams and rivers. Sites were selected from coal mines in Alberta's mountains and foothills, and included resloped dumps of different configurations and ages, and having different vegetation covers. The study concluded that the average annual amount of surface erosion is minimal. As expected, erosion was greatest on slopes which were newly regraded. Slopes with dense grass cover showed no signs of erosion. Generally, the amount of erosion decreased with time, as a result of initial loss of fine particles, the formation of a weathered surface, and increased vegetative cover.

41. **RRTAC 87-9: Hydrogeology and Groundwater Chemistry of the Battle River Mining Area. M.R. Trudell, R.L. Faught and S.R. Moran. 97 pp. No longer available.**

This report describes the premining geologic conditions in the Battle River coal mining area including the geology as well as the groundwater flow patterns, and the groundwater quality of a sequence of several water-bearing formations extending from the surface to a depth of about 100 metres.

42. **RRTAC 87-10: Soil Survey of the Plains Hydrology and Reclamation Project - Battle River Project Area. T.M. Macyk and A.H. MacLean. 62 pp. plus 8 maps. $10.00**

The report evaluates the capability of post-mining landscapes and assesses the changes in capability as a result of mining, in the Battle River mining area. Detailed soils information is provided in the report for lands adjacent to areas already mined as well as for lands that are destined to be mined. Characterization of the reconstructed soils in the reclaimed areas is also provided. Data were collected from 1979 to 1985. Eight maps supplement the report.

43. **RRTAC 87-11: Geology of the Highvale Study Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 78 pp. $10.00**

The report is one of a series that describes the geology, soils and groundwater conditions at the Highvale Coal Mine study site. The purpose of the study was to establish a summary of site geology to a level of detail necessary to provide a framework for studies of hydrogeology and reclamation.

44. **RRTAC 87-12: Premining Groundwater Conditions at the Highvale Site. M.R. Trudell and R. Faught. 83 pp. No longer available.**

This report presents a detailed discussion of the premining flow patterns, hydraulic properties, and isotopic and hydrochemical characteristics of five layers within the Paskapoo Geological Formation, the underlying sandstone beds of the Upper Horseshoe Canyon Formation, and the surficial glacial drift.

45. **RRTAC 87-13: An Agricultural Capability Rating System for Reconstructed Soils. T.M. Macyk. 27 pp. $5.00**

This report provides the rationale and a system for assessing the agricultural capability of reconstructed soils. Data on the properties of the soils used in this report are provided in RRTAC 86-2.

46. **RRTAC 88-1: A Proposed Evaluation System for Wildlife Habitat Reclamation in the Mountains and Foothills Biomes of Alberta: Proposed Methodology and Assessment Handbook. T.R. Eccles, R.E. Salter and J.E. Green. 101 pp. plus appendix. $10.00**

The report focuses on the development of guidelines and procedures for the assessment of reclaimed wildlife habitat in the Mountains and Foothills regions of Alberta. The technical section provides background documentation including a discussion of reclamation planning, a listing of reclamation habitats and associated key wildlife species, conditions required for development, recommended revegetation species, suitable reclamation techniques, a description of the recommended assessment techniques and a glossary of basic terminology. The assessment handbook section contains basic information necessary for evaluating wildlife habitat reclamation, including assessment scoresheets for 15 different reclamation habitats, standard methodologies for measuring habitat variables used as assessment criteria, and minimum requirements for certification. This handbook is intended as a field manual that could potentially be used by site operators and reclamation officers. The study was co-funded with The Coal Association of Canada.

47. **RRTAC 88-2: Plains Hydrology and Reclamation Project: Spoil Groundwater Chemistry and its Impacts on Surface Water. M.R. Trudell (Compiler). 135 pp. No longer available.**

Two reports comprise this volume. The first "Chemistry of Groundwater in Mine Spoil, Central Alberta," describes the chemical make-up of spoil groundwater at four mines in the Plains of Alberta. It explains the nature and magnitude of changes in groundwater chemistry following mining and reclamation. The second report, "Impacts of Surface Mining on Chemical Quality of Streams in the Battle River Mining Area," describes the chemical quality of water in streams in the Battle River mining area, and the potential impact of groundwater discharge from surface mines on these streams.

48. **RRTAC 88-3: Revegetation of Oil Sands Tailings: Growth Improvement of Silver-berry and Buffalo-berry by Inoculation with Mycorrhizal Fungi and N_2-Fixing Bacteria. S. Visser and R.M. Danielson. 98 pp. $10.00**

The report provides results of a study: (1) To determine the mycorrhizal affinities of various actinorrhizal shrubs in the Fort McMurray, Alberta region; (2) To establish a basis for justifying symbiont inoculation of buffalo-berry and silver-berry; (3) To develop a growing regime for the greenhouse production of mycorrhizal, nodulated silver-berry and buffalo-berry; and, (4) To conduct a field trial on reconstructed soil on the Syncrude Canada Limited oil sands site to critically evaluate the growth performance of inoculated silver-berry and buffalo-berry as compared with their un-inoculated counterparts.

49. **RRTAC 88-4: Plains Hydrology and Reclamation Project: Investigation of the Settlement Behaviour of Mine Backfill. D.R. Pauls (compiler). 135 pp. $10.00**

This three part volume covers the laboratory assessment of the potential for subsidence in reclaimed landscapes. The first report in this volume, "Simulation of Mine Spoil Subsidence by Consolidation Tests," covers laboratory simulations of the subsidence process particularly as it is influenced by resaturation of mine spoil. The second report, "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta," describes a series of laboratory tests to determine the behaviour of overburden materials when brought into contact with water. The report entitled "Classification System for Transitional Materials: Plains Region of Alberta," describes a lithological classification system developed to address the characteristics of the smectite rich, clayey transition materials that make up the overburden in the Plains of Alberta.

50. **RRTAC 88-5: Ectomycorrhizae of Jack Pine and Green Alder: Assessment of the Need for Inoculation, Development of Inoculation Techniques and Outplanting Trials on Oil Sand Tailings. R.M. Danielson and S. Visser. 177 pp. No longer available.**

The overall objective of this research was to characterize the mycorrhizal status of Jack Pine and Green Alder which are prime candidates as reclamation species for oil sand tailings and to determine the potential benefits of mycorrhizae on plant performance. This entailed determining the symbiont status of container-grown nursery stock and the quantity and quality of inoculum in reconstructed soils, developing inoculation techniques and finally, performance testing in an actual reclamation setting.

51. **RRTAC 88-6: Reclamation Research Annual Report - 1987. Reclamation Research Technical Advisory Committee. 67 pp. No longer available.**

This annual report describes the expenditure of $500,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

52. **RRTAC 88-7: Baseline Growth Performance Levels and Assessment Procedure for Commercial Tree Species in Alberta's Mountains and Foothills. W.R. Dempster and Associates Ltd. 66 pp. $5.00**

Data on juvenile height development of lodgepole pine and white spruce from cut-over or burned sites in the Eastern Slopes of Alberta were used to define reasonable expectations of early growth performance as a basis for evaluating the success of reforestation following coal mining. Equations were developed predicting total seedling height and current annual height increment as a function of age and elevation. Procedures are described for applying the equations, with further adjustments for drainage class and aspect, to develop local growth performance against these expectations. The study was co-funded with The Coal Association of Canada.

53. **RRTAC 88-8: Alberta Forest Service Watershed Management Field and Laboratory Methods. A.M.K. Nip and R.A. Hursey. 4 Sections, various pagings. $10.00**

Disturbances such as coal mines in the Eastern Slopes of Alberta have the potential for affecting watershed quality during and following mining. The collection of hydrometric, water quality and hydrometeorologic information is a complex task. A variety of instruments and measurement methods are required to produce a record of hydrologic inputs and outputs for a watershed basin. There is a growing awareness and recognition that standardization of data acquisition methods is required to ensure data comparability, and to allow comparison of data analyses. The purpose of this manual is to assist those involved in the field of data acquisition by outlining methods, practices and instruments which are reliable and recognized by the International Organization for Standardization.

54. **RRTAC 88-9: Computer Analysis of the Factors Influencing Groundwater Flow and Mass Transport in a System Disturbed by Strip Mining. F.W. Schwartz and A.S. Crowe. 78 pp. No longer available.**

Work presented in this report demonstrates how a groundwater flow model can be used to study a variety of mining-related problems such as declining water levels in areas around the mine as a result of dewatering, and the development of high water tables in spoil once resaturation is complete. This report investigates the role of various hydrogeological parameters that influence the magnitude, timing, and extent of water level changes during and following mining at the regional scale. The modelling approach described here represents a major advance on existing work.

55. **RRTAC 88-10: Review of Literature Related to Clay Liners for Sump Disposal of Drilling Wastes. D.R. Pauls, S.R. Moran and T. Macyk. 61 pp. No longer available.**

The report reviews and analyses the effectiveness of geological containment of drilling waste in sumps. Of particular importance was the determination of changes in properties of clay materials as a result of contact with highly saline brines containing various organic chemicals.

56. **RRTAC 88-11: Highvale Soil Reconstruction Project: Five Year Summary. D.N. Graveland, T.A. Oddie, A.E. Osborne and L.A. Panek. 104 pp. $10.00**

This report provides details of a five year study to determine a suitable thickness of subsoil to replace over minespoil in the Highvale plains coal mine area to ensure return of agricultural capability. The study also examined the effect of slope and aspect on agricultural capability. This study was funded and managed with industry assistance.

57. **RRTAC 88-12: A Review of the International Literature on Mine Spoil Subsidence. J.D. Scott, G. Zinter, D.R. Pauls and M.B. Dusseault. 36 pp. $10.00**

The report reviews available engineering literature relative to subsidence of reclaimed mine spoil. The report covers methods for site investigation, field monitoring programs and lab programs, mechanisms of settlement, and remedial measures.

58. **RRTAC 89-1: Reclamation Research Annual Report - 1988. 74 pp. $5.00**

This annual report describes the expenditure of $280,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

59. **RRTAC 89-2: Proceedings of the Conference: Reclamation, A Global Perspective. D.G. Walker, C.B. Powter and M.W. Pole (Compilers). 2 Vols., 854 pp. No longer available.**

Over 250 delegates from all over the world attended this conference held in Calgary in August, 1989. The proceedings contains over 85 peer-reviewed papers under the following headings: A Global Perspective; Northern and High Altitude Reclamation; Fish & Wildlife and Rangeland Reclamation; Water; Herbaceous Revegetation; Woody Plant Revegetation and Succession; Industrial and Urban Sites; Problems and Solutions; Sodic and Saline Materials; Soils and Overburden; Acid Generating Materials; and, Mine Tailings.

60. **RRTAC 89-3: Efficiency of Activated Charcoal for Inactivation of Bromacil and Tebuthiuron Residues in Soil. M.P. Sharma. 38 pp. ISBN 0-7732-0878-X. $5.00**

Bromacil and Tebuthiuron were commonly used soil sterilants on well sites, battery sites and other industrial sites in Alberta where total vegetation control was desired. Activated charcoal was found to be effective in binding the sterilants in greenhouse trials. The influence of factors such as herbicide:charcoal concentration ratio, soil texture, organic matter content, soil moisture, and the time interval between charcoal incorporation and plant establishment were evaluated in the greenhouse.

61. **RRTAC 89-4: Manual of Plant Species Suitability for Reclamation in Alberta - 2nd Edition. Hardy BBT Limited. 436 pp. ISBN 0-7732-0882-8. $10.00.**

This is an updated version of RRTAC Report 80-5 which describes the characteristics of 43 grass, 14 forb and 34 shrub and tree species which make them suitable for reclamation in Alberta. The report has been updated in several important ways: a line drawing of each species has been added; the range maps for each species have been redrawn based on an ecosystem classification of the province; new information (to 1990) has been added, particularly in the sections on reclamation use; and the material has been reorganized to facilitate information retrieval. Of greatest interest is the performance chart that precedes each species and the combined performance charts for the grass, forb, and shrub/tree groups. These allow the reader to pick out at a glance species that may suit their particular needs. The report was produced with the assistance of a grant from the Recreation, Parks and Wildlife Foundation.

62. **RRTAC 89-5: Battle River Soil Reconstruction Project Five Year Summary. L.A. Leskiw. 188 pp. No longer available.**

This report summarizes the results of a five year study to investigate methods required to return capability to land surface mined for coal in the Battle River area of central Alberta. Studies were conducted on: the amounts of subsoil required, the potential of gypsum and bottom ash to amend adverse soil properties, and the effects of slope angle and aspect. Forage and cereal crop growth was evaluated, as were changes in soil chemistry, density and moisture holding characteristics.

63. **RRTAC 89-6: Detailed Sampling, Characterization and Greenhouse Pot Trials Relative to Drilling Wastes in Alberta. T.M. Macyk, F.I. Nikiforuk, S.A. Abboud and Z.W. Widtman. 228 pp. No longer available.**

This report summarizes a three-year study of the chemistry of freshwater gel, KCl, NaCl, DAP, and invert drilling wastes, both solids and liquids, from three regions in Alberta: Cold Lake, Eastern Slopes, and Peace River/Grande Prairie. A greenhouse study also examined the effects of adding various amounts of waste to soil on grass growth and soil chemistry. Methods for sampling drilling wastes are recommended.

64. **RRTAC 89-7: A User's Guide for the Prediction of Post-Mining Groundwater Chemistry from Overburden Characteristics. M.R. Trudell and D.C. Cheel. 55 pp. $5.00**

This report provides the detailed procedure and methodology that is required to produce a prediction of post-mining groundwater chemistry for plains coal mines, based on the soluble salt characteristics of overburden materials. The fundamental component of the prediction procedure is the geochemical model PHREEQE, developed by the U.S. Geological Survey, which is in the public domain and has been adapted for use on personal computers.

65. **RRTAC 90-1: Reclamation Research Annual Report - 1989. 62 pp. No longer available.**

This annual report describes the expenditure of $480,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

66. **RRTAC 90-2: Initial Selection for Salt Tolerance in Rocky Mountain Accessions of Slender Wheatgrass and Alpine Bluegrass. R. Hermesh, J. Woosaree, B.A. Darroch, S.N. Acharya and A. Smreciu. 40 pp. $5.00**

Selected lines of slender wheatgrass and alpine bluegrass collected from alpine and subalpine regions of Alberta as part of another native grass project were evaluated for their ability to emerge in a saline medium. Eleven slender wheatgrass and 72 alpine bluegrass lines had a higher percentage emergence than the Orbit Tall Wheatgrass control (a commonly available commercial grass). This means that as well as an ability to grow in high elevation areas, these lines may also be suitable for use in areas where saline soil conditions are present. Thus, their usefulness for reclamation has expanded.

67. **RRTAC 90-3: Natural Plant Invasion into Reclaimed Oil Sands Mine Sites. Hardy BBT Limited. 65 pp. $5.00**

Vegetation data from reclaimed sites on the Syncrude and Suncor oil sands mines have been summarized and related to site and factors and reclamation methods. Natural invasion into sites seeded to agronomic grasses and legumes was minimal even after 15 years. Invasion was slightly greater in sites seeded to native species, but was greatest on sites that were not seeded. Invasion was mostly from agronomic species and native forbs; native shrub and tree invasion was minimal.

68. **RRTAC 90-4: Physical and Hydrological Characteristics of Ponds in Reclaimed Upland Landscape Settings and their Impact on Agricultural Capability. S.R. Moran, T.M. Macyk, M.R. Trudell and M.E. Pigot, Alberta Research Council. 76 pp. $5.00**

The report details the results and conclusions from studying a pond in a reclaimed upland site in Vesta Mine. The pond formed as a result of two factors: (1) a berm which channelled meltwater into a series of subsidence depressions, forming a closed basin; and (2) low hydraulic conductivity in the lower subsoil and upper spoil as a result of compaction during placement and grading which did not allow for rapid drainage of ponded water. Ponds such as this in the reclaimed landscape can affect agricultural capability by: (1) reducing the amount of farmable land (however, the area covered by these ponds in this region is less than half of that found in unmined areas); and, (2) creating the conditions necessary for the progressive development of saline and potentially sodic soils in the area adjacent to the pond.

69. **RRTAC 90-5: Review of the Effects of Storage on Topsoil Quality. Thurber Consultants Ltd., Land Resources Network Ltd., and Norwest Soil Research Ltd. 116 pp. $10.00**

The international literature was reviewed to determine the potential effects of storage on topsoil quality. Conclusions from the review indicated that storage does not appear to have any severe and longterm effects on topsoil quality. Chemical changes may be rectified with the use of fertilizers or manure. Physical changes appear to be potentially less serious than changes in soil quality associated with the stripping and respreading operations. Soil biotic populations appear to revert to pre-disturbance levels of activity within acceptable timeframes. Broad, shallow storage piles that are seeded to acceptable grass and legume species are recommended; agrochemical use should be carefully controlled to ensure soil biota are not destroyed.

70. **RRTAC 90-6: Proceedings of the Industry/Government Three-Lift Soils Handling Workshop. Deloitte & Touche. 168 pp. $10.00**

This report documents the results of a two-day workshop on the issue of three-lift soils handling for pipelines. The workshop was organized and funded by RRTAC, the Canadian Petroleum Association and the Independent Petroleum Association of Canada. Day one focused on presentation of government and industry views on the criteria for three-lift, the rationale and field data in support of three- and two-lift procedures, and an examination of the various soil handling methods in use. During day two, five working groups discussed four issues: alternatives to three-lift; interim criteria and suggested revisions; research needs; definitions of terms. The results of the workshop are being used by a government/industry committee to revise soils handling criteria for pipelines.

71. **RRTAC 90-7: Reclamation of Disturbed Alpine Lands: A Literature Review. Hardy BBT Limited. 209 pp. $10.00**

This review covers current information from North American sources on measures needed to reclaim alpine disturbances. The review provides information on pertinent Acts and regulations with respect to development and environmental protection of alpine areas. It also discusses: alpine environmental conditions; current disturbances to alpine areas; reclamation planning; site and surface preparation; revegetation; and, fertilization. The report also provides a list of research and information needs for alpine reclamation in Alberta.

72. **RRTAC 90-8: Plains Hydrology and Reclamation Project: Summary Report. S.R. Moran, M.R. Trudell, T.M. Macyk and D.B. Cheel. 105 pp. $10.00**

This report summarizes a 10-year study on the interactions of groundwater, soils and geology as they affect successful reclamation of surface coal mines in the plains of Alberta. The report covers: Characterization of the Battle River and Wabamun study areas; Properties of reclaimed materials and landscapes; Impacts of mining and reclamation on post-mining land use; and, Implications for reclamation practice and regulation. This project has led to the publication of 18 RRTAC reports and 22 papers in conference proceedings and referred journals.

73. **RRTAC 90-9: Literature Review on the Disposal of Drilling Waste Solids. Monenco Consultants Limited. 83 pp. $5.00**

This report reviews the literature on, and government and industry experience with, burial of drilling waste solids in an Alberta context. The review covers current regulations in Alberta, other provinces, various states in the US and other countries. Definitions of various types of burial are provided, as well as brief summaries of other possible disposal methods. Environmental concerns with the various options are presented as well as limited information on costs and monitoring of burial sites. The main conclusion of the work is that burial is still a viable option for some waste types but that each site and waste type must be evaluated on its own merits.

74. **RRTAC 90-10: Potential Contamination of Shallow Aquifers by Surface Mining of Coal. M.R. Trudell, S.R. Moran and T.M. Macyk. 75 pp. $5.00**

This report presents the results of a field investigation of the movement of salinized groundwater from a mined and reclaimed coal mine near Forestburg into an adjacent unmined area. The movement is considered to be an unusual occurrence resulting from a combination of a hydraulic head that is higher in the mined area than in the adjacent coal aquifer, and the presence of a thin surficial sand aquifer adjacent to the mine. The high hydraulic head results from deep ponds in the reclaimed landscape that recharge the base of the spoil.

75. **RRTAC 91-1: Reclamation Research Annual Report - 1990. Reclamation Research Technical Advisory Committee. 69 pp. No longer available.**

This annual report describes the expenditure of $499 612 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program. The report lists the 70 research reports published under the program.

76. **RRTAC 91-2: Winter Soil Evaluation and Mapping for Regulated Pipelines. A.G. Twardy. 43 pp. ISBN 0-7732-0874-7. $5.00**

Where possible, summer soil evaluations are preferred for pipelines. However, when winter soil evaluations must be done, this report lays out the constraints and requirements for obtaining the best possible information. Specific recommendations include: restricting evaluations to the time of day with the best light conditions; use of core- or auger-equipped drill-trucks; increased frequency of site inspections and soil analyses; and, hiring a well-qualified pedologist. The province's soils are divided into four classes, based on their difficulty of evaluation in winter: slight (most soils); moderate; high; and, severe (salt-affected soils in the Brown and Dark Brown Soil Zones).

77. **RRTAC 91-3: A User Guide to Pit and Quarry Reclamation in Alberta. J.E. Green, T.D. Van Egmond, C. Wylie, I. Jones, L. Knapik and L.R. Paterson. 151 pp. ISBN 0-7732-0876-3. $10.00**

Sand and gravel pits or quarries are usually reclaimed to the original land use, especially if that was better quality agricultural or forested land. However, there are times when alternative land uses are possible. This report outlines some of the alternate land uses for reclaimed sand and gravel pits or quarries, including: agriculture, forestry, wildlife habitat, fish habitat, recreation, and residential and industrial use. The report provides a general introduction to the industry and to the reclamation process, and then outlines some of the factors to consider in selecting a land use and the methods for reclamation. The report is <u>not</u> a detailed guide to reclamation; it is intended to help an operator determine if a land use would be suitable and to guide him or her to other sources of information.

78. **RRTAC 91-4: Soil Physical Properties in Reclamation. M.A. Naeth, D.J. White, D.S. Chanasyk, T.M. Macyk, C.B. Powter and D.J. Thacker. 204 pp. ISBN 0-7732-0880-1. $10.00**

This report provides information from the literature and Alberta sources on a variety of soil physical properties that can be measured on reclaimed sites. Each property is explained, measurement methods, problems, level of accuracy and common soil values are presented, and methods of dealing with the property (prevention, alleviation) are discussed. The report also contains the results of a workshop held to discuss soil physical properties and the state-of-the-art in Alberta.

79. **RRTAC 92-1: Reclamation of Sterilant Affected Sites: A Review of the Issue in Alberta. M. Cotton and M.P. Sharma. 64 pp. ISBN 0-7732-0884-4. No longer available**

This report assesses the extent of sterilant use on oil and gas leases in Alberta, identifies some of the concerns related to reclamation of sterilant affected sites and the common methods for reclaiming these sites, and outlines the methods for sampling and analyzing soils from sterilant affected sites. The report also provides an outline of a research program to address issues raised by government and industry staff.

80. **RRTAC 92-2: Reclamation Research Annual Report - 1991. Reclamation Research Technical Advisory Committee. 55 pp. ISBN 0-7732-0888-7. No longer available.**

This report describes the expenditure of $485,065 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the five program areas, and describes the projects funded under each program. It also lists the 75 research reports that have been published to date.

81. **RRTAC 92-3: Proceedings of the Industry/Government Pipeline Reclamation Success Measurement Workshop. R.J. Mahnic and J.A. Toogood. 62 pp. ISBN 0-7732-0886-0. $5.00.**

This report presents the results of a workshop to identify the soil and vegetation parameters that should be used to assess reclamation success on pipelines in Alberta. Six soil parameters (topsoil admixing; topsoil replacement thickness; compaction; soil loss by erosion; texture; and salinity) and six vegetation parameters (plant density; species composition; ground cover; vigour; weeds/undesirable species; and rooting characteristics) were selected as most important. Working groups discussed these parameters and presented suggested methods for assessing them in the field.

82. **RRTAC 92-4: Oil Sands Soil Reconstruction Project Five Year Summary. HBT AGRA Limited. 109 pp. ISBN 0-7732-0875-5. $10.00**

This report documents a five year study of the effects of clay and peat amendments to oil sand tailings sand on survival and growth of trees and shrubs. Ten species (jack pine, white spruce, serviceberry, silverberry, buffaloberry, pin cherry, prickly/woods rose, Northwest poplar, green alder, and Bebb willow) were planted into tailings sand amended with three levels of peat and three levels of clay. The treatments were incorporated to a depth of 20 cm or 40 cm. Data are provided on plant survival and growth, root size and distribution, disease and small mammal damage, herbaceous cover, soil moisture, soil chemistry, and bulk density.

83. **RRTAC 92-5: A Computer Program to Simulate Groundwater Flow and Contaminant Transport in the Vicinity of Active and Reclaimed Strip Mines: A User's Guide. A.S. Crowe and F.W. Schwartz, SIMCO Groundwater Research Ltd. 104 pp. plus appendix. ISBN 0-7732-0877-1. NOTE: This report is only available from the Alberta Research Council, Publications Centre, 250 Karl Clark Road, P.O. Box 8330, Station F, EDMONTON, Alberta T6H 5R7 as ARC Information Series 119. The cost is $20.00 and the cheque must be made out to the Alberta Research Council.**

The manual describes a computer program that was developed to study the influence of coal strip mining on groundwater flow systems and to simulate the transport of generated contaminants, both spatially and in time, in the vicinity of a mine. All three phases of a strip mine can be simulated: the pre-mining regional groundwater flow system; the mining and reclamation phase; and, the post-mining water level readjustment phase. The model is sufficiently general to enable the user to specify virtually any type of geological conditions, mining scenario, and boundary conditions.

84. **RRTAC 92-6: Alberta Drilling Waste Sump Chemistry Study. Volume I: Report (Volume II: Appendices is only available through the Alberta Research Council, Publications Centre, 250 Karl Clark Road, P.O. Box 8330, Station F, EDMONTON, Alberta T6H 5R7. The cost is $15.00 and the cheque must be made out to the Alberta Research Council.). T.M. Macyk, S.A. Abboud and F.I. Nikiforuk, Alberta Research Council. 217 pp. ISBN 0-7732-0879-8. $10.00.**

This study synthesizes the data from sampling and analysis of the solids and liquids found in 128 drilling waste sumps across Alberta. Drilling waste types sampled included: 72 freshwater gel, 19 invert, 27 KCl, 2 NaCl, and 8 others. Data and statistics are tabulated by waste type, depth of the drill hole, and ERCB administrative region for both the solids and the liquids. Using preliminary loading limits developed by the government/industry Drilling Waste Review Committee, the report presents information on the volume and depth of waste that could be landspread, and the area required for landspreading. The oil and gas industry provided approximately $585,000 for the sampling and analysis phase of this study.

85. **RRTAC 93-1: Reclamation of Native Grasslands in Alberta: A Review of the Literature. D.S. Kerr, L.J. Morrison and K.E. Wilkinson, Environmental Management Associates. 205 pp. plus appendices. ISBN 0-7732-0881-X. $10.00.**

A review of the literature on native grassland reclamation was conducted to summarize the current state of knowledge on reclamation and restoration efforts within Alberta. The review is comprehensive, including an overview of the regulations and guidelines governing land use on native prairie; a description of the dominant grassland ecoregions in Alberta; a review of the common disturbance types, extent and biophysical effects of disturbance on native prairie within Alberta; a description of the factors which influence the degree of disturbance and reclamation; and examples of both natural and enhanced recovery of disturbed sites through the examination of selected case studies.

86. **RRTAC 93-2: Reclamation Research Annual Report - 1992. Reclamation Research Technical Advisory Committee. 56 pp. ISBN 0-7732-0883-6. $5.00.**

This report describes the expenditure of $474,705 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and the research strategies of the five programs, and describes the projects funded under each program. It also lists the 85 research reports that have been published to date.

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